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HF MODEM FEASIBILITY DEMONSTRATION

Harris Corporation

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The objective of this program was to evaluate a recently developed, bandwidth efficient, channel-adaptive digital modem for radio communications below 30 MHz (High Frequency (HF)). The block and bit error performance during simplex operation was characterized over both Harris Corporation and RADC's HF simulators. Performance for 2.4, 3.6, and 4.8 kb/s in a 3 kHz channel was obtained on both HF simulators while performance at 8 and 16 kbps in a 6 kHz channel was obtained only on Harris

HF simulator.

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1.0 INTRODUCTION

1.1 Objective

The objective of this program was to evaluate a recently developed bandwidth efficient, channel-adaptive digital modem for radio communications below 30 MHz (High Frequency, HF). Existing and proposed requirements (for greater communication reliability, lower error rates, and higher signalling rates) now exceed the present operational capability of modems currently in use.

The subject modem was developed at Harris Corporation's Communication Systems Division under several Independent Research and Development (IR&D) programs over the past 3 years. The modem is implemented as a standalone, programmable (via included control firmware) signal processor sufficient to interface directly with conventional HF transceivers.

The block and bit error performance during simplex operation as a function of various simulated HF channel parameters was characterized for 2.4 kb/s, 3.6 kb/s, and 4.8 kb/s in a 3 kHz channel and 8.0 kb/s and 16 kb/s in a 6 kHz channel.

1.2 Approach

The program consisted of two main phases. During the first phase, the modem was tested at the Harris GCSD facilities in Melbourne, Florida, utilizing the near real-time HF simulator. During these tests, the modem was operated with an AMC 29/05 development system which provided writable control store for both the modem and simulator software, and automatically ran and recorded the results of a series of tests with differing HF channel parameters.

During the second phase, the modem was tested utilizing RADC's HF simulator located in RADC's DICEF facility. During these tests, the modem operated as a self-contained unit, with all software residing in PROM's and bit rates selected by front panel switches.

The 6 kHz channel bit rates were not tested during this second phase of the program due to bandwidth limitations of the simulator at DICEF.

1.3 Results

There were two major objectives to be achieved by this study. The first was an extensive characterization of the performance of the Harris narrowband HF modem operating over numerous simulated HF channel conditions at several data throughput rates. The second objective was to determine whether performance characterizations utilizing the Harris near real-time HF channel simulator coincide with performance characterizations utilizing the DICEF simulator. These objectives have been met with excellent results. The performance of the Harris HF modem at data rates of 2.4 kb/s and 4.8 kb/s, which had not been characterized previously, were better than had been anticipated. Table 1.3-1 summarizes the overall performance characterization by tabulating the sets of HF channel parameters required to achieve a bit error rate of 0.5 percent. The results reported by Watterson[1] for the USC-10 and ACQ-6 modems (2.4 kb/s) are also included for comparison.

[1] "H.F. Channel-Simulator Measurements and Performance Analyses on the USC-10, ACQ-6, and MX-190 PSK Modems," C.C. Watterson and C.M. Minister, July 1975, U.S. Department of Commerce Report, OT 75-56.

Table 1.3-1. Performance Comparison Between USC-10, ACQ-6 and Harris Modem at BER = 5×10^{-3}

TYPE OF CHANNEL	USC-10	ACQ-6	HARRIS 2.4	HARRIS 4.8	HARRIS 8.0
1 Path, 0.2 Hz DS (Sp/N)	29.5 dB	29.5 dB	23.3 dB (20.8 dB)	26.6 dB (23.8 dB)	31.5 dB
1 Path, 1 Hz DS (Sp/N)	29.5 dB	30.5 dB	24.3 dB (22.6 dB)	27.7 dB (26.8 dB)	31.5 dB
2 Path, 0.2 Hz DS (Sp/N)	30.0 dB	29.7 dB	18.6 dB (14.9 dB)	23.2 dB (21.7 dB)	24.0 dB
2 Path, 1.0 Hz DS (Sp/N)	30.8 dB	29.8 dB	18.8 dB (18.7 dB)	25.4 dB (24.0 dB)	27.2 dB
1 Path, S/N = ∞ (DS)	2.88 Hz	2.28 Hz	5.35 Hz (4.8 Hz)	3.52 Hz (3.6 Hz)	3.4 Hz
2 Paths, S/N = ∞ (DS)	1.80 Hz	2.20 Hz	4.28 Hz (3.4 Hz)	1.67 Hz (1.7 Hz)	2.3 Hz
2 Paths, DS = 1.0 Hz S/N = ∞ (MS)	2.70 ms	3.05 ms	6.70 ms (6.5 ms)	4.35 ms (5.5 ms)	4.85 ms

An error rate of 0.5 percent was chosen for this table since the USC-10 and ACQ-6 cannot achieve an error rate of 0.1 percent under most of these channel conditions as shown in Table 1.3-2. Since the limiting factor of HF transmitters is the peak output power, the signal-to-noise (Sp/N) represents the ratio of the peak transmitter power required to the noise power in a 2.4 kHz bandwidth (2.4 kHz noise bandwidth for the 8.0 kb/s mode, also, i.e., fixed peak power and N_0). These numbers are the same as E_{pb}/N_0 for the 2.4 kb/s mode, and 3.0 dB higher than E_{pb}/N_0 for the 4.8 kb/s mode, and 5.2 db higher for the 8 kb/s mode. The peak-to-average power ratio for the USC-10 and ACQ-6 (parallel tone modems) has been assumed to be 7.0 dB and for the Harris Modem (single carrier PSK), 1.0 dB. For the Harris Modem, the number in parenthesis corresponds to the performance data obtained utilizing the DICEF simulator, and the number preceding it corresponds to the Harris near real-time simulator results.

1.3.1 Harris Modem Performance Compared to the USC-10 and ACQ-6

Comparing the Harris HF modem to the USC-10 and ACQ-6, one observes that the Harris modem operating in the 2.4 kb/s mode will provide the same performance under significantly more severe HF channel conditions. Typically, the Harris modem is capable of tolerating a 10 times greater noise level or more than twice the Doppler Spread or multipath spread. If the comparison were made on an average power basis (rather than peak power) giving up 6.0 dB, the Harris Modem would still provide superior performance. It should be noted that this performance gain is obtained without giving up the immediate recovery from fades or from a simplex link turn-around as is provided by the USC-10 and ACQ-6.

Table 1.3-2. Performance Comparison Between USC-10, ACQ-6 and Harris Modem at BER = 1.0×10^{-3}

TYPE OF CHANNEL	USC-10	ACQ-6	HARRIS 2.4	HARRIS 4.8	HARRIS 8.0
1 Path, 0.2 Hz DS (Sp/N)	37.5 dB	36.7 dB	30.1 dB (27.8 dB)	33.3 dB (27.8 dB)	40.9 dB
1 Path, 1.0 Hz DS (Sp/N)	∞*	∞*	33.0 dB (32.2 dB)	38.0 dB (38.2 dB)	41.2 dB
2 Paths, 0.2 Hz DS (Sp/N)	∞*	37.3 dB	22.1 dB (19.3 dB)	27.4 dB (21.5 dB)	27.7 dB
2 Paths, 1.0 Hz DS (Sp/N)	∞*	∞*	25.5 dB (24.0 dB)	∞* (33.2 dB)	34.7 dB
1 Path, $E_{pb}/N_o = \infty$ (DS)	1.0 Hz	1.0 Hz	2.27 Hz (2.6 Hz)	1.4 Hz (1.7 Hz)	1.8 Hz
2 Paths, $E_{pb}/N_o = \infty$ (DS)	0*	1.0 Hz	2.6 Hz (1.9 Hz)	0.9 Hz (1.1 Hz)	1.3 Hz
2 Paths, $E_{pb}/N_o = \infty$ (MS) DS = 1.0Hz	0*	0*	6.5 ms (6.50 ms)	1.9 ms (5.5 ms)	4.2 ms

*10^{-3} BER not achievable

The results of the simulations also indicate that the Harris Modem operating in the 4.8 kb/s mode utilizing the same peak power and bandwidth as the USC-10 and ACQ-6 (2.4 kb/s) can tolerate worse HF channel conditions, yet provide twice the data rate with the same BER performance. Only the dual path, irreducible error (S/N = ∞) Doppler Spread capability (maximum of 1.7 Hz to achieve a BER of 0.5 percent) of the Harris Modem at 4.8 kb/s is slightly worse than the USC-10 (1.8 Hz) and ACQ-6 (2.2 Hz). The Doppler Spread observed on actual HF links is, however, usually less than 1.0 Hz. The more relevant criterion for predicting performance on actual HF links is the modem's ability to tolerate multipath spread while achieving good BER Versus Sp/N performance at Doppler Spreads up to 1.0 Hz.

For HF radios that can provide a 6 kHz bandwidth to permit the Harris Modem to operate at 8 kb/s, the table also indicates that performance comparable to or better than the USC-10 or ACQ-6 can be achieved for more than three times data rate without increasing the transmitter peak power. The only weaker area of the 8 kb/s mode is the single fading path performance. Pure single fading path HF channels are not, however, often encountered in practical experience. A second path 10 to 20 dB down is usually present in actual channels characterized as single path.

1.3.2 Evaluation of the Harris Near Real-Time Simulator

Comparing the performance charactizations of the Harris and DICEF simulators, one can observe very similar results. The Sp/N performance in most cases was slightly better when the DICEF simulator was used. The more severe transmit and receive filters in the Harris simulator are likely to be the major cause of this discrepancy. This finding suggests that transmit and receive filters with the characteristics of typical military HF radios should be added to the DICEF simulator. The addition of an AGC to the DICEF simulator would also appear to be desirable.

The performance as a function of the Doppler Spread (DS) and the Multipath Spread (MS) is also very similar on both simulators. Based on these findings, we conclude that HF modem evaluations using the Harris near real-time internal HF channel simulators will yield results that would be essentially equivalent to those that would be obtained using the DICEF simulator.

1.4 Report Organization

The HF modem and near real-time HF channel simulator are described in Section 2.0. The test programs with detailed results of both phases of this program are presented in Section 3.0. Recommendations based upon test results are presented in Section 4.0.

2.0 HF MODEM/SIMULATOR

The HF modem has been developed and constructed to permit two modes of operation. In the first of these, the modem, shown in Figures 2.0-1 and 2.0-2, may be directly connected to the analog interfaces of an HF exciter and receiver for over-the-air operation/link tests or to the analog interfaces of an HF channel simulator such as the one in RADC's DICEF facilities (used in the second phase of testing on this program). In this mode of operation, the data input and output ports are operational for passing data at the selected rate and making BER measurements. Alternatively, the HF modem may operate in a near real-time mode alternating between the role of modem and HF channel simulator utilizing software developed to model the simulator described by Watterson,[1] et al.

The analog interfaces are bypassed in this mode of operation since the "demodulated" inphase and quadrature components can be directly passed between the modem and simulation program. To simulate the effects of transmitter and receiver filters, 10-pole Tchebychev filters (digitally implemented) are utilized at the input and output of the channel simulation as shown in Paragraph 2.2. During this mode of operation, the bit and block error rates are also measured by the simulator software. The modem software for this mode is essentially identical to the real-time software except for the modifications necessary to bypass the I/O operations to the analog and data interfaces.

A more detailed description of the modem and simulator operation and hardware implementation is presented in the following sections.

[1] "HF Channel-Simulator Measurements and Performance Analysis on the USC-10, ACQ-6, and MX-190 PSK Modems," C.C. Watterson, C.M. Minister, July 1975, U.S. Department of Commerce Report, OT 75-56.

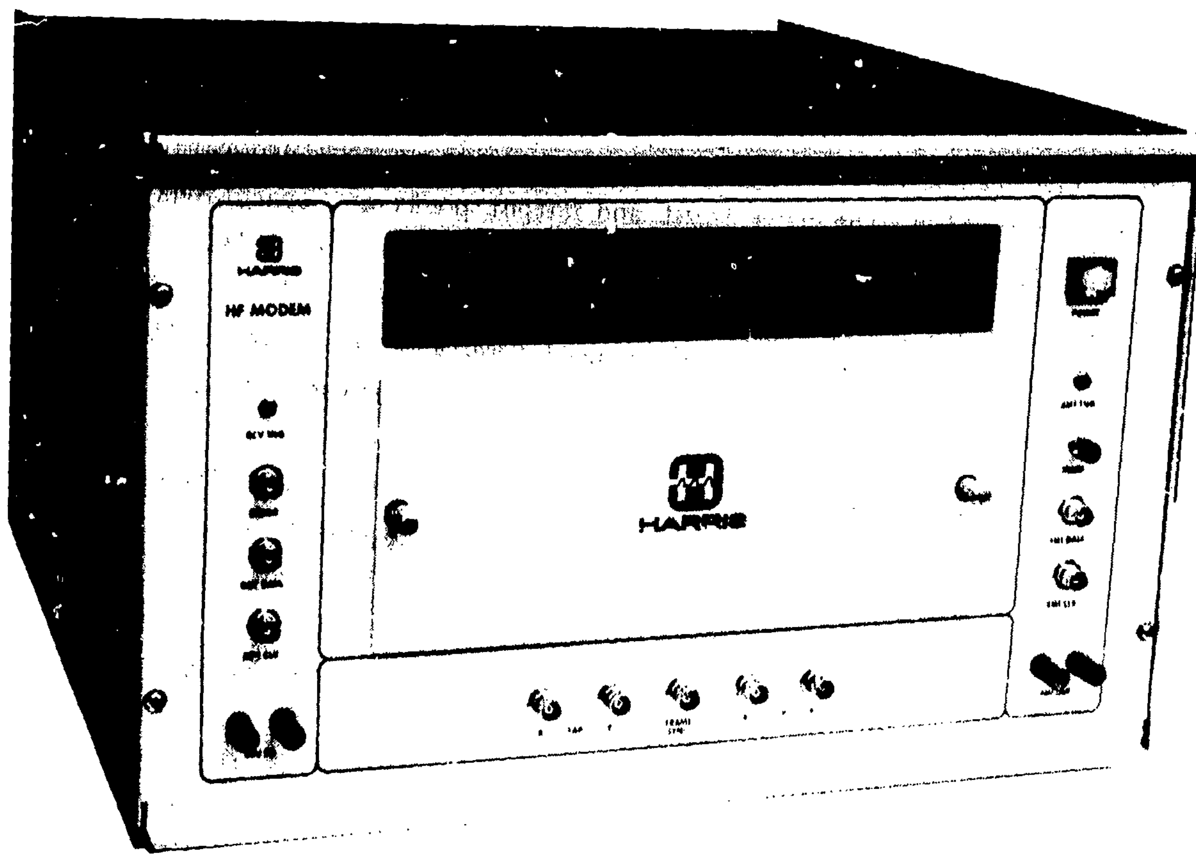

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Figure 2.0-1. HF Modem

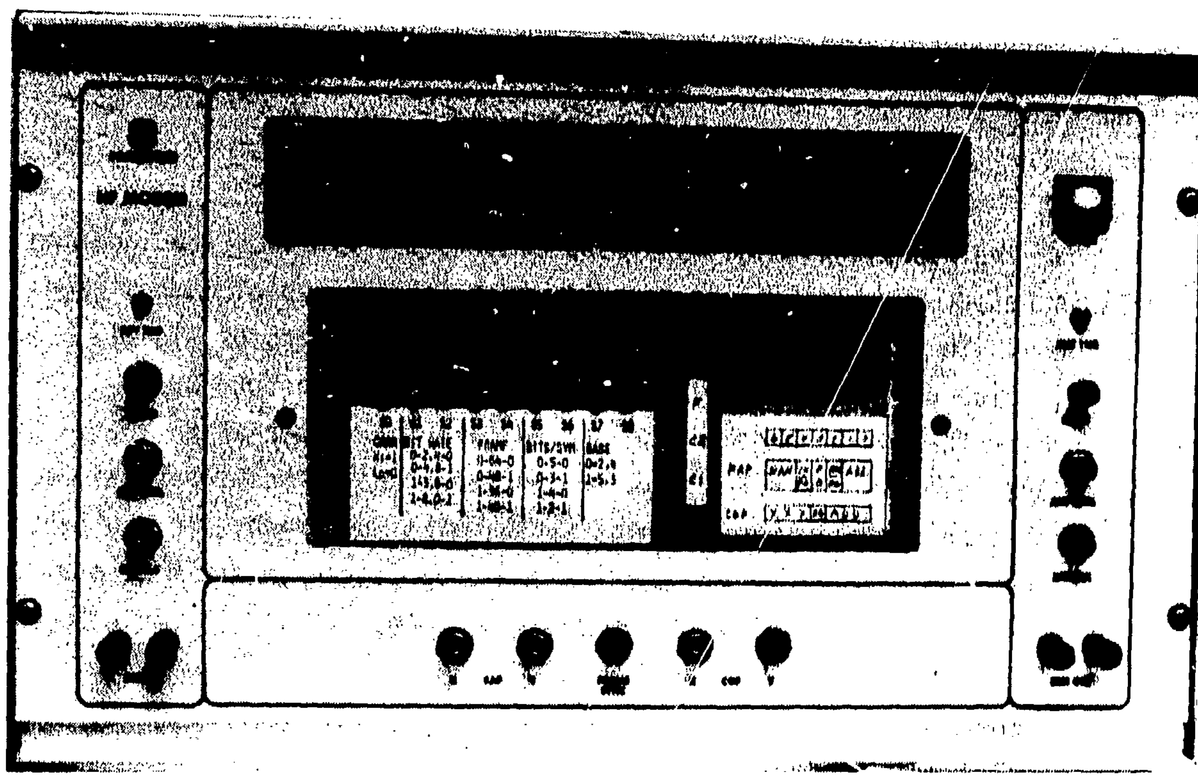

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Figure 2.0-2. HF Modem With Controls Exposed

2.1 Functional Modem Design

The basic modem design approach consists of a data mode and a training mode. The receiver functions performed during the training mode are as follows: the channel weight estimates are made, the receiver determines the frequency offset of the signal, establishes frame timing, and refines this timing so that channel equalization can be effectively accomplished in the data mode. The transmitter transmits different formats during these two modes, but of course the transmit mode and receive mode in a particular modem are not slaved to one another unless the modem is looped.

The receiver in the data mode continually examines the incoming signal to detect a training signal and switches to the training mode when this occurs. This operation removes requirements of a loss of signal detector, which on an HF channel is likely to adversely affect the performance. The training mode has a fixed duration, after which the receiver automatically switches back to the data mode. Thus the receiver, after completion of reception, remains in the data mode ready for the next transmission. We will first discuss the modem operation in the data mode and then discuss the operation in the training mode.

2.1.1 Data Mode Operation

In this section we will discuss the data mode operation of the modem used to obtain the data in Section 3.0. We first consider the case of 3.6 kb/s transmission and then discuss the modifications necessary to run at 2.4 kb/s, 4.8 kb/s, 8 kb/s, and 16 kb/s.

The transmitted format at 3.6 kb/s consists of frames of data, with a frame defined as 20 consecutive known symbols followed by 20 consecutive unknown symbols. Each symbol is 8-phase PSK and hence each frame contains 60 information bits. The symbol rate is 2.4 kHz designed to operate in a 3 kHz bandwidth. Thus the frame length is 16.67 milliseconds, half of which is known data and half unknown data. The 8.33 milliseconds of known data serves as a "guard band" for multipath delay spread introduced by the channel. Thus the allowable multipath spread, plus the memory time of the transmit and received filters, should not exceed 8.33 ms.

The 2.4 kb/s operation is achieved by using 4-phase PSK (QPSK) rather than the 8-phase PSK used in the 3.6 kb/s mode. All other parameters remain identical.

The 4.8 kb/s mode retains the 8-phase signal format of 3.6 kb/s, but achieves the higher rate by reducing the number of known symbols to 16 and increasing the number of unknown symbols to 32 on a per frame basis. The frame length is thus increased to 48 symbols and the number of weights tracking the channel must be reduced to 17. The "guard time" between data (unknown) symbols is reduced to 6.67 msec from 8.33 msec. The 4.8 kb/s mode should therefore theoretically not be able to tolerate quite as much multipath delay spread as either 2.4 kb/s or 3.6 kb/s.

The 8 kb/s mode for operation over a 6 kHz channel utilizes the 8-phase PSK signal format with the symbol rate increased to 5.333 k-baud. The number of known and unknown symbols per frame are both increased to 32, resulting in a frame length of 64. Although this provides a greater number of known symbols during the "guard time", this "guard time" is reduced to 6.0 msec because of the higher symbol rate.

The 16 kb/s mode is achieved by utilizing a 64 point QAM signal format, thus doubling (to six) the number of bits transmitted per symbol. All other processing remains identical to the 8 kb/s mode.

2.1.2 Acquisition Mode

Upon initiation of a "train" button, the transmitter sends approximately 1 second of a sine wave displaced from the carrier by one-fourth the symbol rate. At the end of the second, the phase of this sine wave is reversed for one frame duration. Following this, the transmitter sets its PN code and sends normal data, but for approximately 3 seconds, it clamps the data input port to zero causing transmission of a known PN sequence. After this time, it proceeds with the normal data mode in which half of the symbols are determined from data exclusive-ORed with the PN sequence.

2.2 Near Real-Time HF Channel Simulator

As a part of the IR&D effort to develop the bandwidth efficient HF modem, it was felt necessary to implement a Near Real-Time Simulator so that the modem could be efficiently checked. During the checkout phase and subsequent phase of investigating new algorithms for the modem, it was discovered that this simulator was not a luxury but actually a necessity. Most new algorithms or parameter variations trade better performance with one type of link disturbance for worse performance when a different type is present. Hence, evaluation under a variety of link conditions must be conducted before an accurate picture can be obtained. Further, each test must run the channel for a sufficient period to allow the fading statistics to become representative. Without this constraint the results can be very misleading.

During the initial phase of the Harris HF modem development, a general purpose computer program was used as the basis of evaluating algorithms. The algorithm selected by this technique turned out to be basically sound but its performance was very far from that of the algorithm previously described. It would have been totally impossible to evolve the original concept to that presently employed without the Near Real-Time Simulator to use as a means of evaluation and synthesis of areas of weakness.

2.2.1 Simulator Capability

Figure 2.2.1 is a functional block diagram of the Harris HF Simulator. It is mathematically modeled after the channel simulation at NTIA described by Watterson, et al[1,2]. The actual channel simulation has three independently faded channels with selectable Doppler frequency shift and time delay available. The fading is caused by multiplication of the delayed signal with a two-dimensional Gaussian vector whose components have been passed through a two-pole Butterworth filter. The Doppler Spread is calculated based upon the "RMS bandwidth" of the filter.

$$D_s = \frac{2\int_0^{\infty} f^2 \, |F(f)|^2 \, df}{\int_0^{\infty} |F(f)|^2 \, dF}$$

where D_s is Doppler Spread and F(f) is the frequency response of the filter. For a two-pole Butterworth filter, this corresponds to twice the 3 dB bandwidth. The simulator at DICEF uses a three-pole filter for this purpose, but channel phase variation statistics can be shown to depend (on a first-order basis) on the Doppler Spread, as defined in the above equation, independent of the shape of F(f). The simulator at NRL[3] uses a second order Butterworth filter like Harris.

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1 "Experimental Verification of an Ionospheric Channel Model", C.C. Watterson, J.R. Juroshek, W.D. Besema, July 1969, U.S. Department of Commerce Report, ERL 112-ITS80.

2 "HF Channel-Simulator Measurements and Performance Analyses on the USC-10, ACQ-6, and MX-190 PSK Modems", C.C. Watterson, C.M. Minister, July 1975, U.S. Department of Commerce Report, OT 75-56.

3 "A Programmable Real-Time HF Channel Simulator", R. Cole, W. Jewett, J. Linnchou Jr.

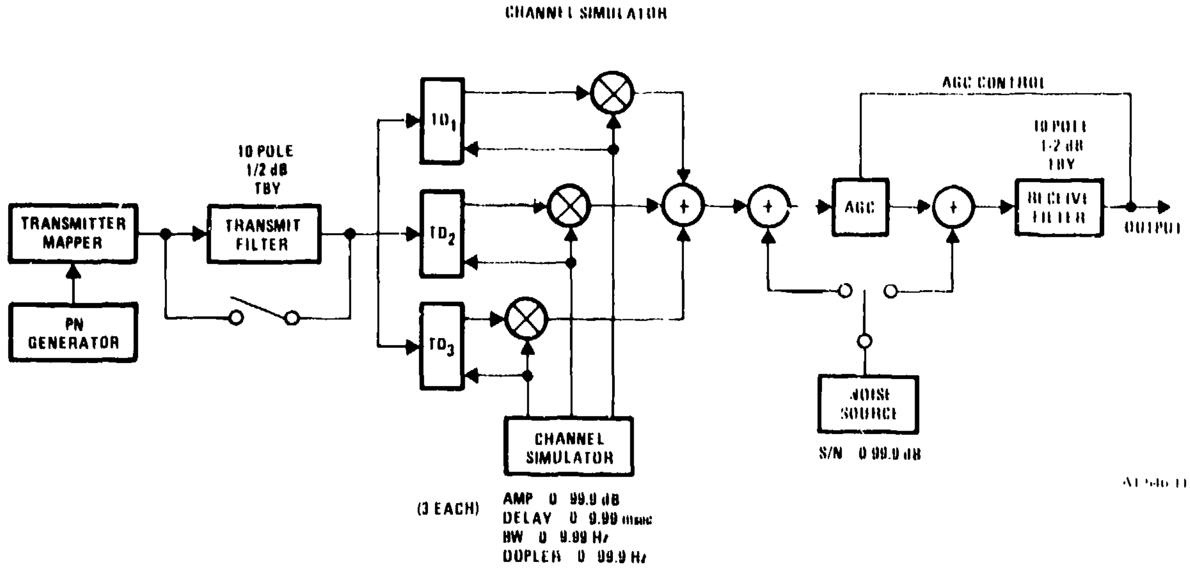

Figure 2.2.1. Channel Simulator

The principal difference between the DICEF simulator and the Harris simulator as shown, is that the RF modulated signal is created as a complex input and the bandpass filters (10-pole, 0.5 dB ripple, Tschebycheff filters) associated with the transmitter and receiver, along with receive AGC, are included in the channel model. The output is a complex demodulated signal representing the result of a QAM demodulator at the receiver. This representation bypasses the need for Hilbert transformers and allows direct evaluation of RF equipment effects without the cumbersome task of obtaining and interfacing this gear. The effect of RF filters was felt to be an essential aspect of the channel disturbance of a high rate serial transmission technique since the "smearing" of the channel impulse response by the filter directly affects the amount of work an equalizer or correlator approach must do to combat channel disturbances.

The particular approach proposed must take this into account when the detailed processing algorithms are selected, since those based upon impulses to represent channel response could easily lead to selections which will eventually work very poorly when interfaced with real equipment.

The simulator is implemented as an additional program in the modem so that the modem takes turns being a link simulator and a modem. This, of necessity, requires non real-time operation. However, this was found to be an advantage since it allowed investigation of algorithms which took too long for a real-time modem. If they were found to be of value, the code was refined to allow real-time operation.

3.0 TEST PROGRAM

The Test Program consisted of two phases. The first phase involved in-plant testing of the HF modem utilizing the Harris near real-time simulator capabilities. The second phase involved testing of the HF modem on the HF channel simulator at RADC's DICEF facility. The purpose for in-plant testing was two-fold. Comparison of the results obtained using identical channel parameters on both the internal simulator and the DICEF simulator would establish the validity of the Harris simulator. This validation is desirable for future developments of the HF modem capabilities. In addition, the DICEF facility cannot test the modem operation over a 6 kHz channel, whereas the Harris simulator can.

The HF modem was therefore tested on both simulators at data rates of 2.4 kb/s, 3.6 kb/s, and 4.8 kb/s. Two different signal formats, to provide 4.8 kb/s, were tested on the internal simulator. One utilized the same frame format as the lower two rates, and a 16-point symbol constellation to provide the increased throughput rate. The other utilized the same 8-phase PSK symbol constellation as 3.6 kb/s, but used an altered frame format with only 33-1/3 percent known symbols (as compared to 50 percent) to achieve the increased throughput rate. Since the latter produced better results on the internal simulator, that was the one tested on the DICEF simulator.

At the 8 Kbps and 16 Kbps data rates, which require a 6 kHz channel bandwidth the modem was tested only on the Harris simulator. The 8 kb/s mode of operation is very similar to the 3.6 kb/s mode with the symbol rate increased to 5.33 k-baud from 2.4 k-baud. The 50 percent overhead (known symbols) frame structure was used with the frame length increased to 64 symbols. The 16 kb/s utilized the same frame format but used an increased symbol constellation of 64 points to achieve the higher throughput rate.

Table 3.0 summarizes the frame and symbol formats utilized for each tested data rate, and the simulator(s) used to test the rate.

Table 3.0. Summary of Data Rates Tested

DATA RATE (KB/S)	SYMBOL RATE (K-BAUD)	CHANNEL BANDWIDTH (KHZ)	FRAME SYMBOL FORMAT		SYMBOL CONSTELLATION (NO. POINTS)	SIMULATOR USED	
			NO. KNOWN	NO. DATA		INTERNAL	DICEF
2.4	2.4	3.0	20	20	4-PSK	YES	YES
3.6	2.4	3.0	20	20	8-PSK	YES	YES
4.8	2.4	3.0	20	20	16-QAM[1]	YES	NO
4.8	2.4	3.0	16	32	8-PSK	YES	YES
8.0	5.33	6.0	32	32	8-PSK	YES	NO
16.0	5.33	6.0	32	32	64-QAM[2]	YES	NO

NOTES

1. 12-Phase Outer Ring, 4-Phase Inner Ring
2. Four Rings of 16 Phases

3.1 Near Real-Time Simulator Tests for a 3 kHz Channel

Tests using the near real-time internal (to the HF modem) HF channel simulator were performed in accordance with the test plan outlined in Appendix A. This section presents performance curves for the data rates which operate over a 3 kHz channel. The performance data for the 4.8 kb/s mode presented in the figures correspond to the 8-phase PSK, 1/3 overhead (16 reference - 32 data symbol per frame) implementation. In all cases, this implementation yielded better performance than the 16-point constellation, 1/2 overhead version. Paragraph 3.3 presents the results for the 6 kHz channel modes.

Performance curves[1] for several multitone modems are also presented for comparison. To provide a realistic basis for comparison, the S/N performance has been normalized to the ratio of peak energy per bit (E_{pb}/N_o) to spectral noise height. A 7 dB peak-to-average ratio has been assumed for all of the multitone modems and a 1 dB peak-to-average ratio has been assumed for the Harris modem. The data on the USC-10, the ACQ-6 and the MX-190 was obtained from measurements reported by Watterson and Minister[1] taken on the NTIA simulator at Boulder, Colorado.

In all cases, the data corresponds to that available on a simplex link without capability of resynchronization. There was never an incident during the gathering of the data presented here in which the Harris modem required resynchronization after the initial synchronization was successful. In all cases, initial synchronization was performed under the same channel conditions used for bit error rate measurements. For a fixed bit rate, the parameters of the Harris modem were the same for all BER data presented. The block error rate data may be utilized to predict the throughput of a near error free ARQ arrangement once the ARQ protocols are established. For the Harris data, block error rate represents the fraction of 1000-bit blocks with one or more errors in them. The block length for the data measured by Watterson at NTIA was defined as 672 bits in length. This provides a measurement advantage to the parallel tone modems since a shorter block leads to lower block error rates.

[1] "H.F. Channel-Simulator Measurements and Performance Analyses on the VSC-10, ACQ-6, and MX-190 PSK Modems," Clark C. Watterson and Carl M. Minister, July 1975, U.S. Department of Commerce Report, OT 75-56.

As may be noted on many of the sets of performance curves of the Harris modem, the 4.8 kb/s performance is better on an E_{pb}/N_o basis than the 3.6 kb/s. This most likely results from the higher data rate being obtained by reduction in the overhead (from 1/2 to 1/3) without changing the signal constellation. Curves for the 16-point 4.8 kb/s implementation (which are not shown) would consistently lie above (poorer performance than) the 3.6 kb/s curves.

Figures 3.1-1, 3.1-2, and 3.1-3 show the performance for a single fading path versus E_{pb}/N_o for Doppler Spreads of 0.2 Hz, 1.0 Hz, and 2.0 Hz, respectively. Figure 3.1-4 shows the irreducible error performance ($E_{pb}/N_o = \infty$) of the modem versus Doppler Spread in Hz. In all of these single fading path characterizations, the Harris modem demonstrates performance superior to the multitone modems in both the 2.4 kb/s and 4.8 kb/s mode. In most cases, the 4.8 kb/s curves are at least 3 dB better than the multitone modems (2.4 kb/s). This indicates that on a peak power limited HF link with a dominant single fading path, the Harris modem could provide twice the data rate with an error rate equal to or better than other existing modems.

Figures 3.1-5, 3.1-6, and 3.1-7 show the performance for two, equal (mean) power fading paths with 1 ms relative delay (multipath spread) versus E_{pb}/N_o at Doppler Spreads of 0.2 Hz, 1.0 Hz and 2.0 Hz, respectively. Figure 3.1-8 shows the irreducible error performance ($E_{pb}/N_o = \infty$) of the modem versus Doppler Spread for this two-path HF channel. Figure 3.1-9 shows the irreducible error performance of the modem versus the multipath spread of two equal (mean) power fading paths, each with a 1 Hz Doppler Spread. Figure 3.1-10 shows the irreducible error performance of the modem versus the difference in the mean Doppler frequency of two equal (mean) power fading paths with a Doppler Spread of 1 Hz and multipath spread (delay) of 1 ms.

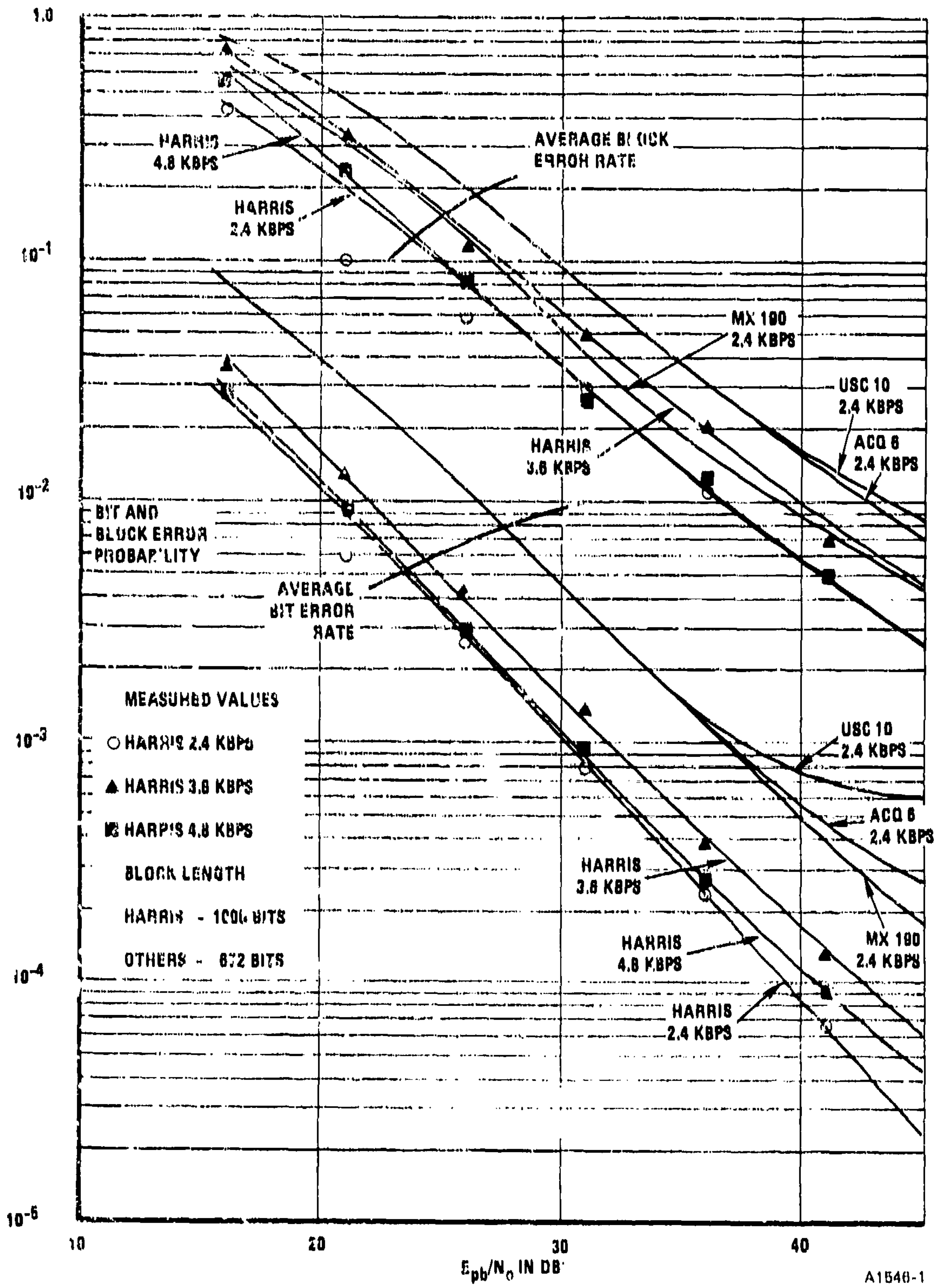

Figure 3.1-1. Single Fading Path, 0.2 Hz Doppler Spread

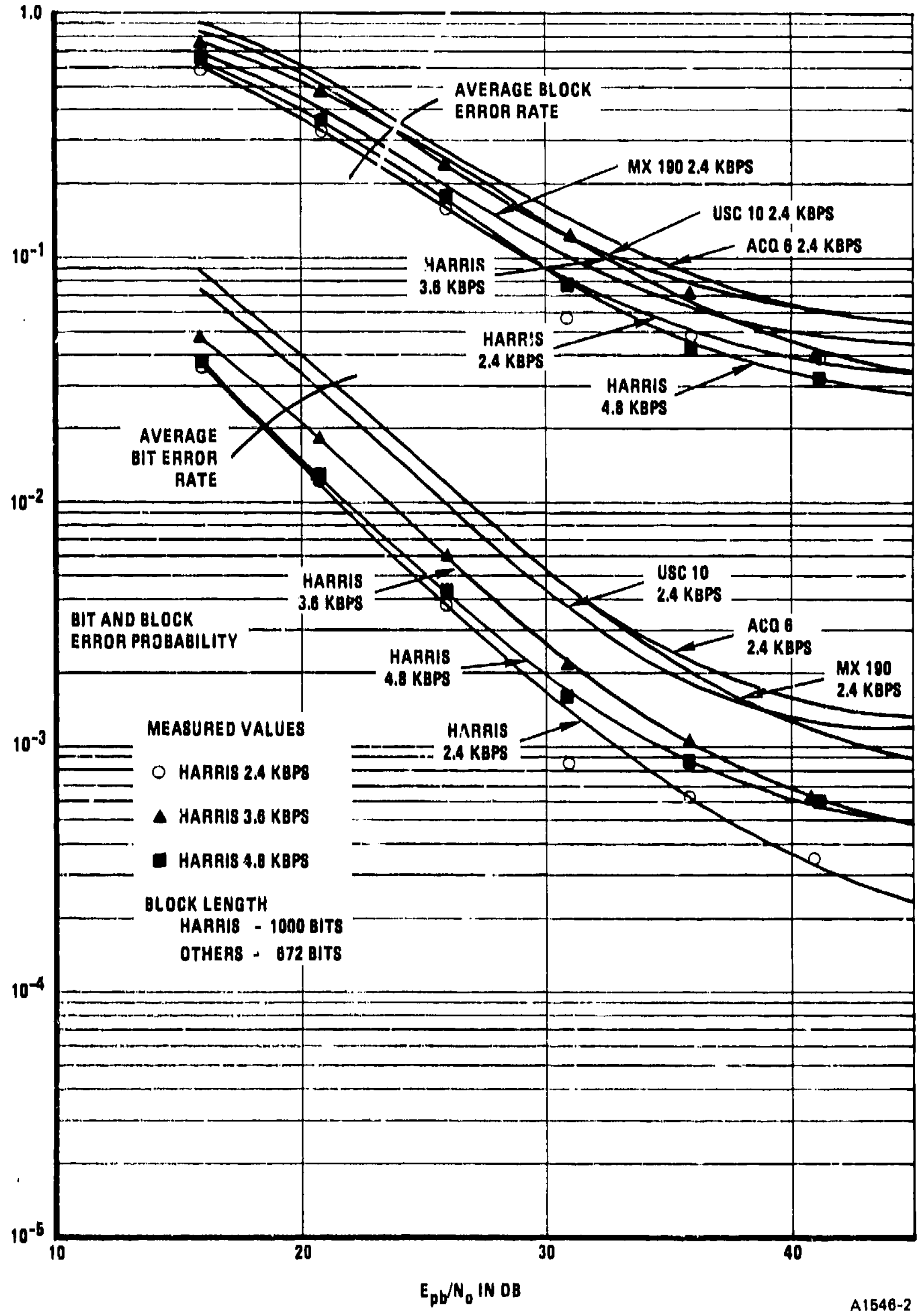

Figure 3.1-2. Single Fading Path, 1.0 Hz Doppler Spread

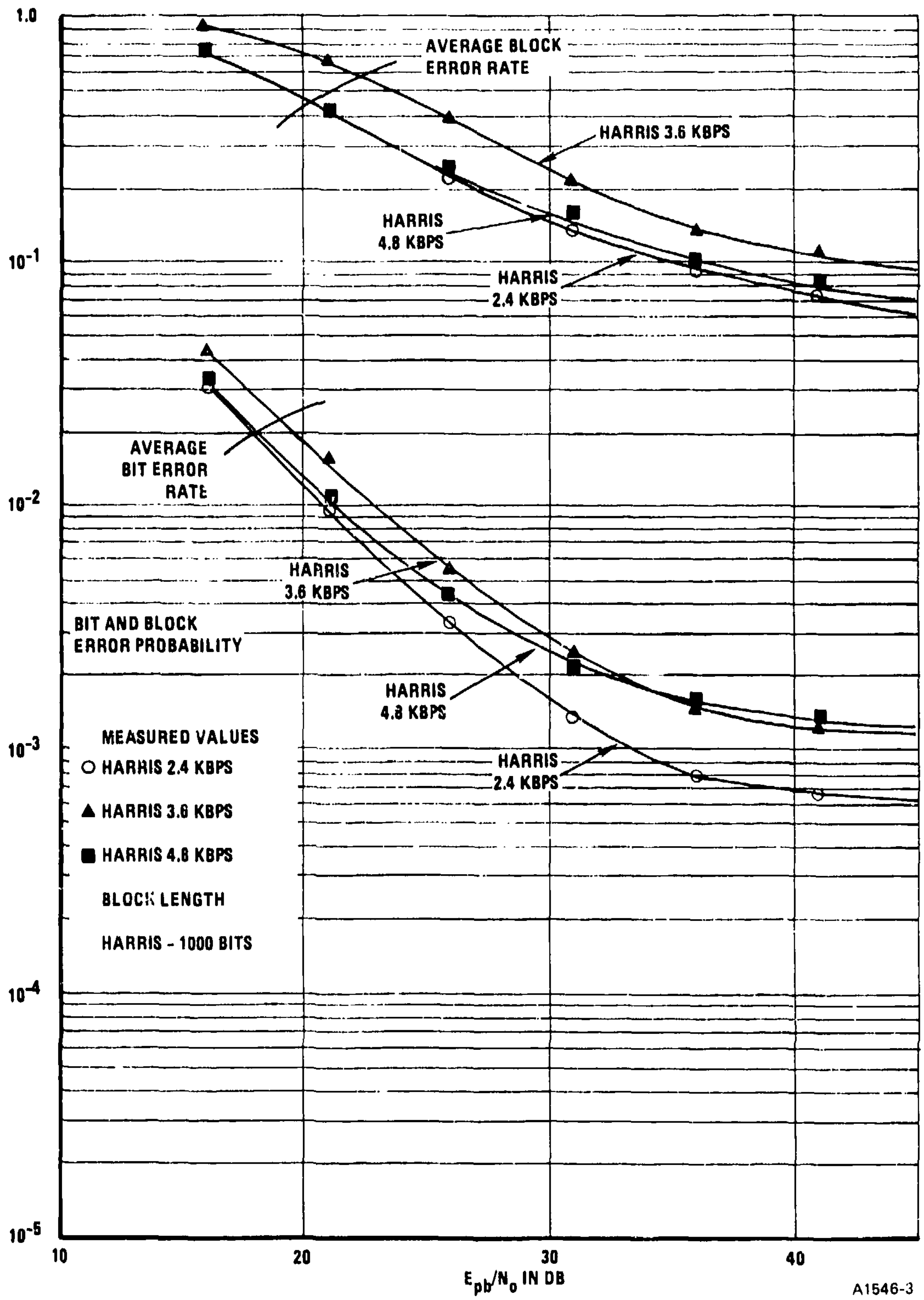

Figure 3.1-3. Single Fading Path, 2.0 Hz Doppler Spread

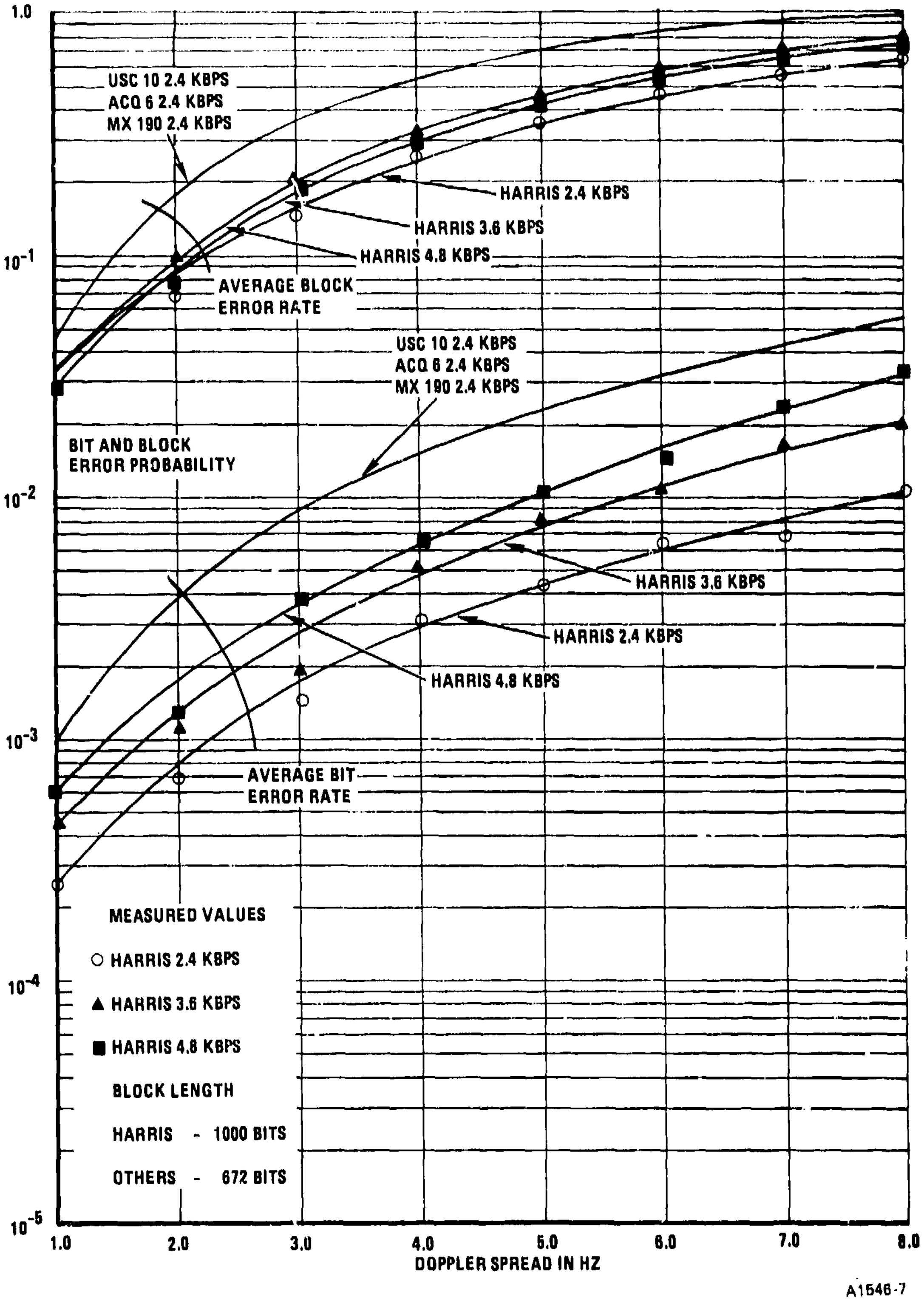

Figure 3.1-4. Single Fading Path, $E_{pb}/N_o = \infty$

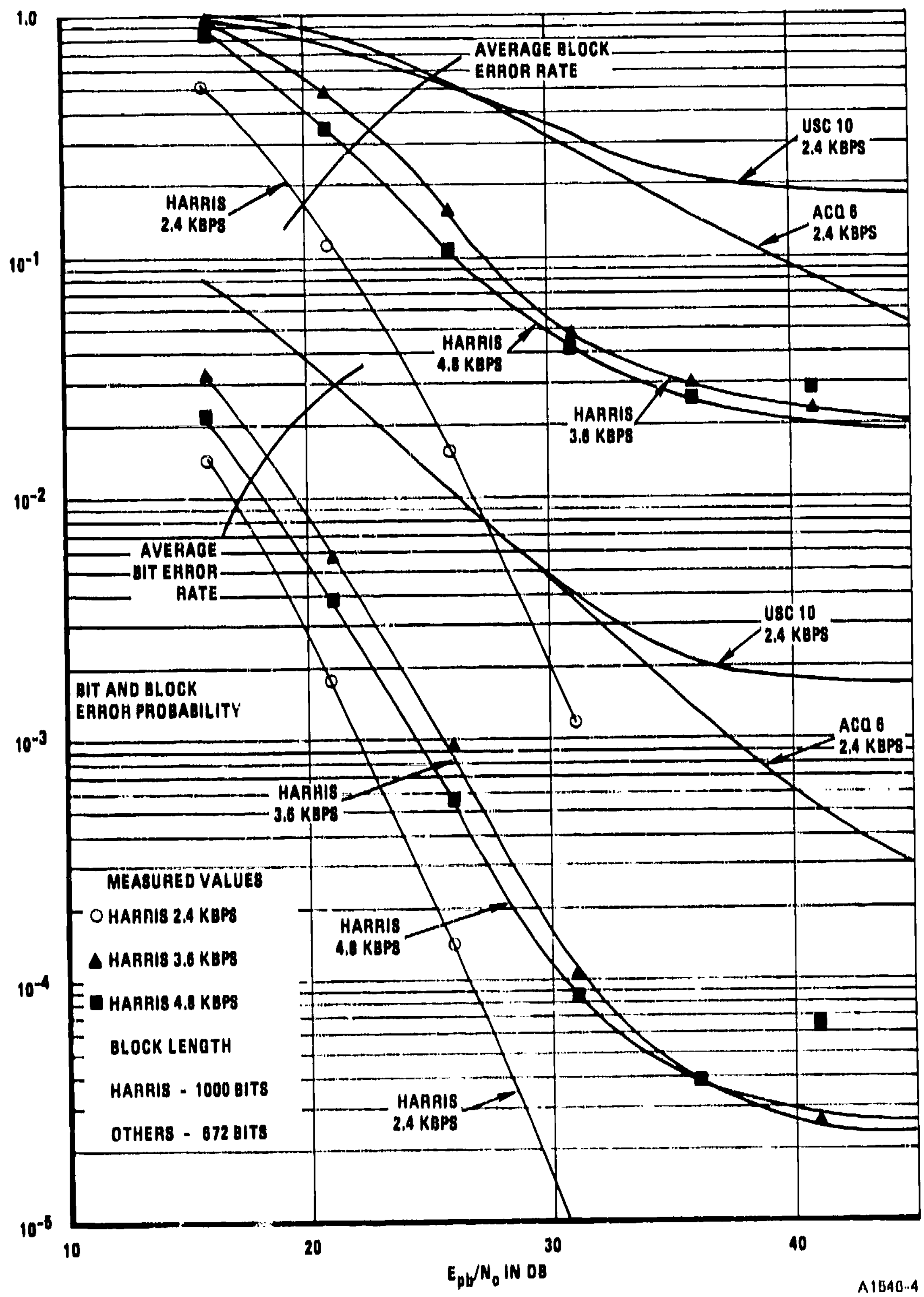

Figure 3.1-5. Two Equal Power Fading Paths With 1 ms Relative Delay, 0.2 Hz Doppler Spread

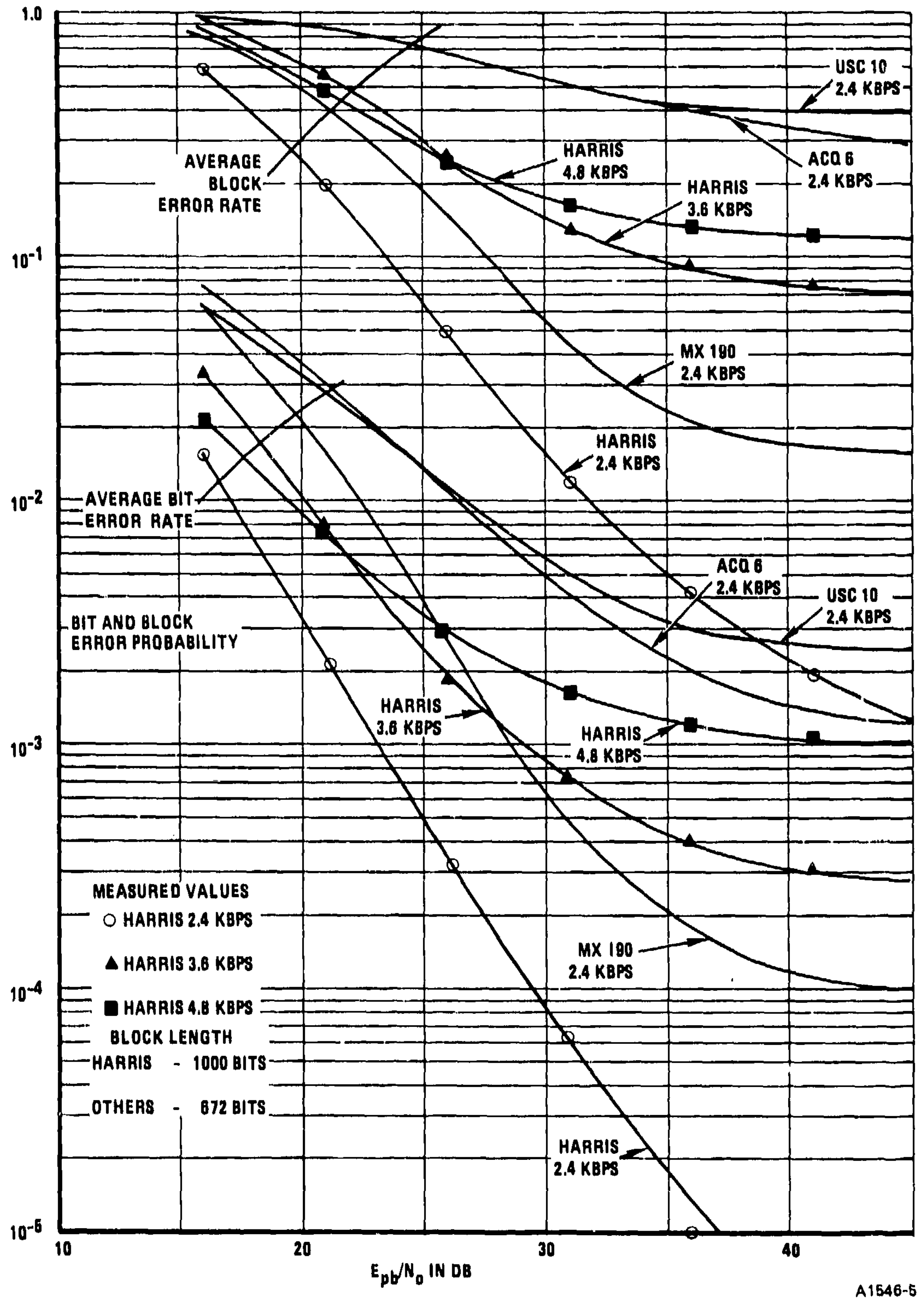

Figure 3.1-6. Two Equal Power Fading Paths With 1 ms Relative Delay, 1.0 Hz Doppler Spread

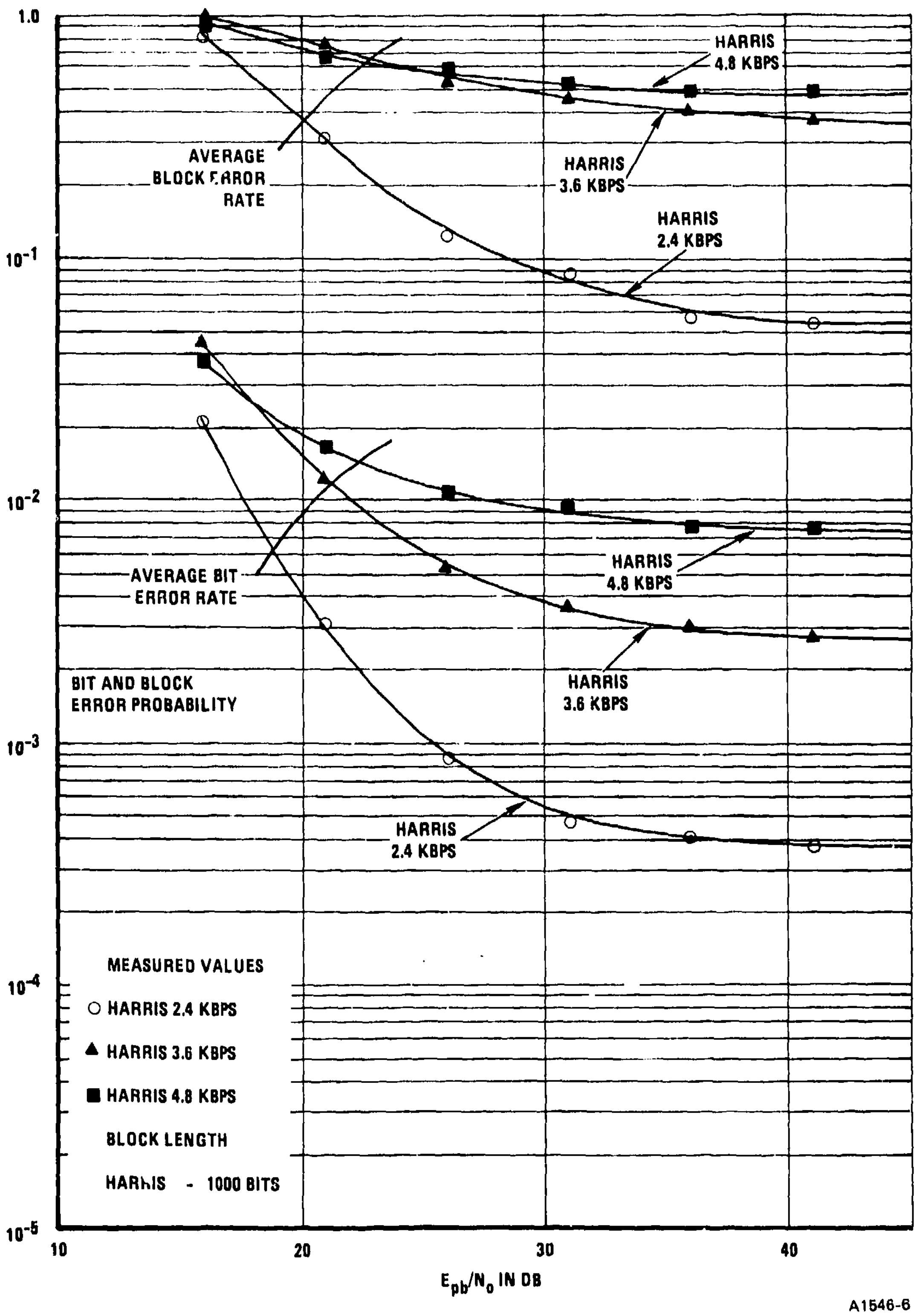

Figure 3.1-7. Two Equal Power Fading Paths With 1 ms Relative Delay, 2.0 Hz Doppler Spread

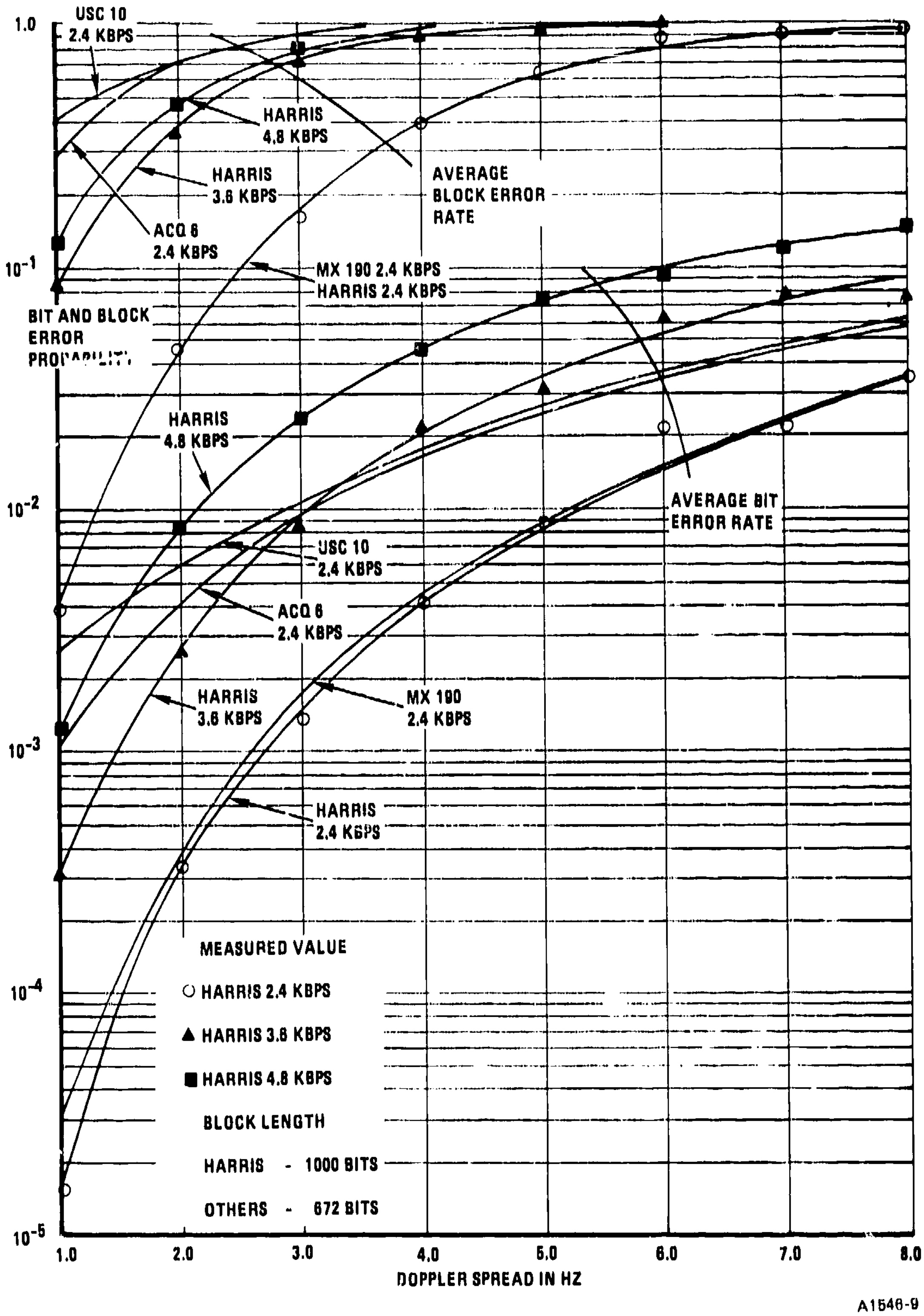

Figure 3.1-8. Two Equal Power Fading Paths With 1 ms Relative Delay, $E_{pb}/N_o = \infty$

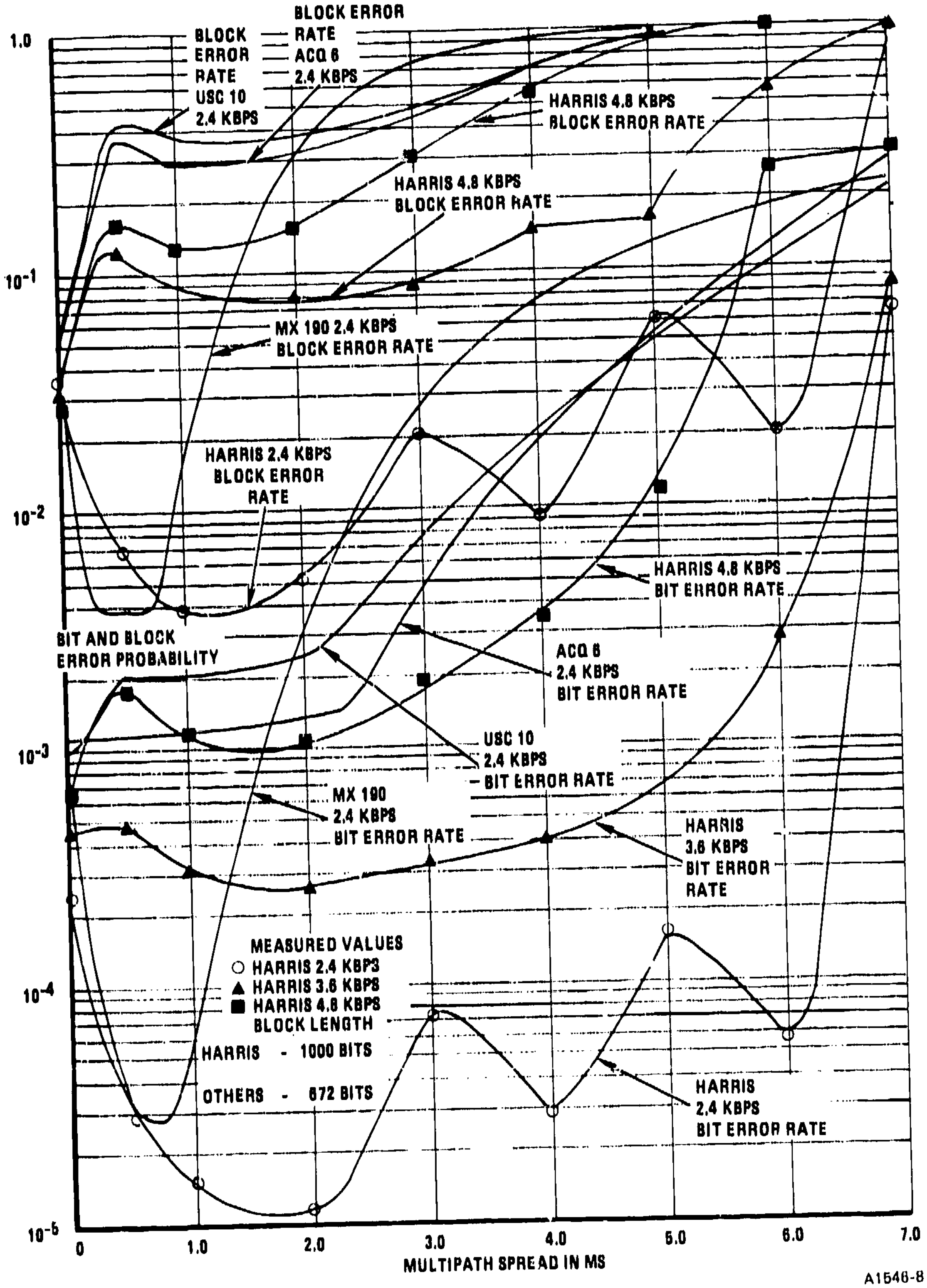

Figure 3.1-9. Two Equal Power Fading Paths With 1 Hz Doppler Spread, $E_{pb}/N_o = \infty$

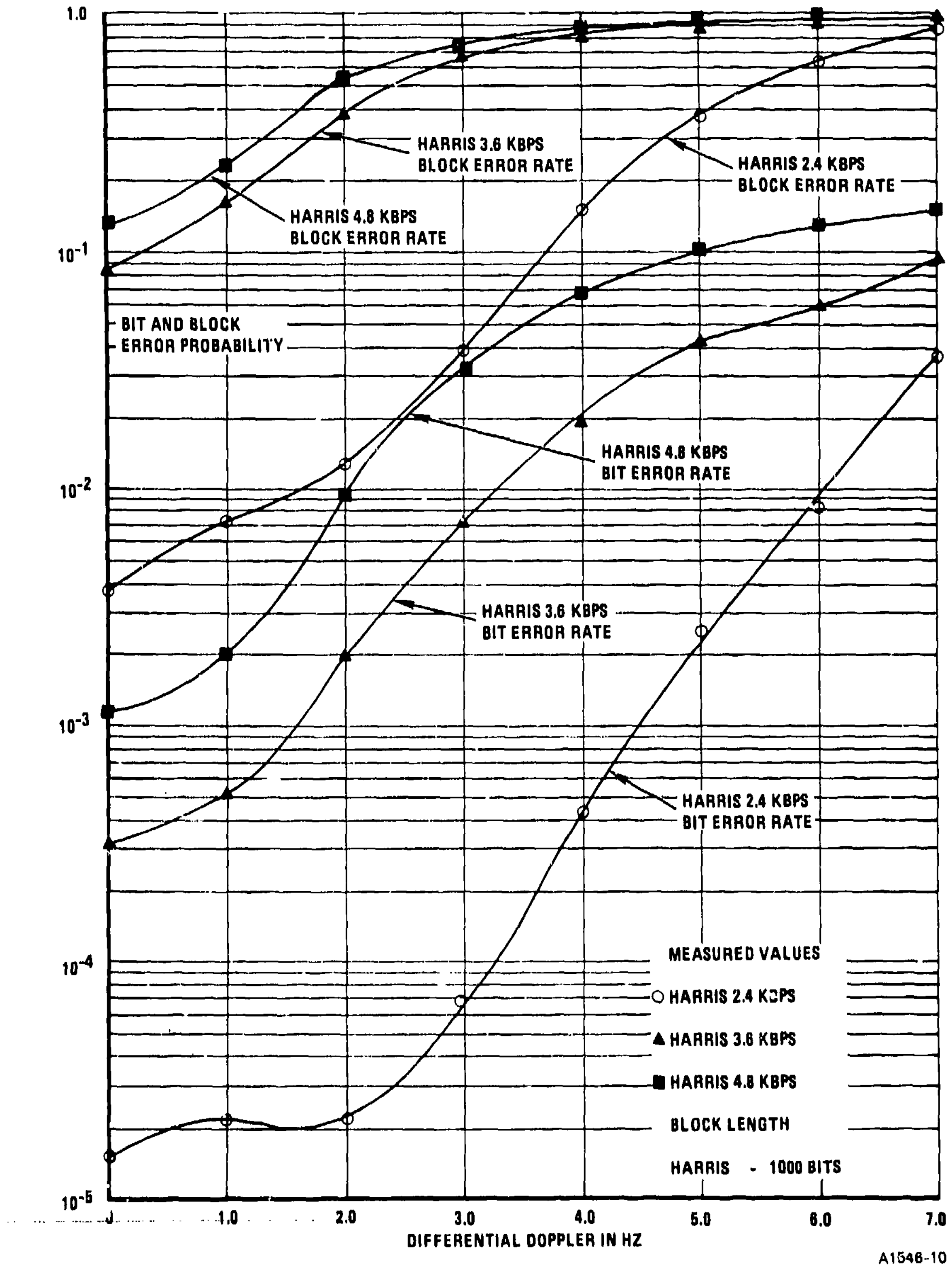

Figure 3.1-10. Two Equal Power Fading Paths With 1 Hz Doppler Spread, 1 ms Relative Delay, and $E_{pb}/N_0 = \infty$

In all of these dual channel simulations, the Harris modem, operating in the 2.4 kb/s mode, achieved performance superior to any of the multitone modems. Under many dual path conditions tested, Harris modem's 4.8 kb/s performance bettered that of the 2.4 kb/s performance of the multitone modems. However, at high S/N ratios, the dual path, Doppler Spread 4.8 kb/s performance above 1 Hz could not match the multitone modem modem performance. This was not unexpected since the lower overhead used in the 4.8 kb/s mode makes the modem less able to accurately track rapidly varying multipath channels. Also, as evidenced in Figure 3.1-9, the multipath spread performance of the 4.8 kb/s mode begins to degrade at approximately 1.5 ms less spread than either 3.6 kb/s or 2.4 kb/s. This was also expected due to the reduced length (by 1.67 ms) of the channel tracking equalizer in the 4.8 kb/s mode.

3.2 DICEF Testing

The second phase of the test program involved taking modem performance data on the HF link simulator in the DICEF facility at RADC. This simulator, like the near real-time simulator at Harris, is mathematically based on the HF link model developed by Watterson[1] at NTIA. The detailed capability of the RADC simulator can be obtained from Rome Air Development Center. It is worthwhile to discuss the differences between the Harris simulator and the RADC simulator so that performance differences can be better understood.

a. The first difference which affects modem performance between the RADC simulator and the Harris simulator is associated with the modem interface. The RADC simulator, which operates in real-time, accepts a real analog baseband signal, samples and digitizes the signal. It then performs the Hilbert transform on the samples to obtain the imaginary part of the complex signal in order to perform the complex arithmetic

[1] Ibid.

necessary to simulate the HF link. The Harris Modem creates the real baseband signal by quadrature modulating a low frequency carrier (1.8 kHz) with filtered D/A versions of the complex modulating signal. The filters are six-pole Butterworth with a 3 dB bandwidth of 1.4 kHz. The Harris simulator, on the other hand, takes the digital versions of the complex modulating signal directly as the complex input to the HF channel. Similarly at the modem receiver, the RADC simulator provides a real analog baseband input which is quadrature demodulated by the modem and then digitized. When operated with the simulator, the digital complex output of the HF channel is taken directly into the modem as the complex output of the quadrature demodulator.

b. If the quadrature modulated signal at 1.8 kHz could be considered to be a "narrowband" signal, these two methods of handling the interface would be equivalent. However, the baseband signal is definitely not "narrowband" and some degradation in performance can be expected from the quadrature modulator-demodulator used with the RADC simulator. The performance with the Harris simulator would correspond to the case where the quadrature modulation and demodulation were done at an IF frequency in the exciter and receiver which was much higher than 3 kHz, hence directly providing a narrowband signal.

c. The second difference, affecting modem performance even more than the first, is the degree to which effects of RF equipment are included in the simulation. All of the data taken at 2.4 kb/s, 3.6 kb/s and 4.8 kb/s on the Harris simulator included simulation of a 10-pole 0.5 dB ripple Tchebycheff bandpass filter to simulate the filter in the HF exciter and simulation of an identical filter operating on the signal after the HF channel to simulate the HF receiver filter. In addition, an AGC function was included which attempted to simulate the receive AGC in the HF receiver. The RADC simulator has no capability of simulating effects of the HF exciter and receiver, and hence the effect of these impairments were not represented in the data taken at DICEF. A hardware AGC was included to simulate the effect of the HF receiver AGC, but no additional filtering was done. As can be seen from the data taken from both simulations, the impairments caused by the exciter and receive filters were greater than that caused by the baseband quadrature modulator-demodulator.

d. A difference, which is anticipated to be minor, is the shape of the lowpass filters used to create the random lowpass complex process to cause Rayleight fading for each received path. In the RADC simulator, the filters are three-pole Butterworth filters and in the Harris simulator, these filters are two-pole Butterworth filters. In both cases, the Doppler Spread is normalized to the RMS bandwidth of the filter (as defined by Watterson) which should cause the performance to be similar for the same entered Doppler Spread. However, some minor difference in performance might occur due to this difference.

e. The RADC simulator includes the capability of including impulsive noise in addition to Gaussian noise, whereas the Harris simulator does not. Hence, curves including impulsive noise were run only at DICEF.

f. The RADC simulator, like the Harris simulator, can allow received paths with three different time delays. The RADC simulator can specify two different paths at each time delay to correspond to the two magnetoionic components of a reflecting medium. The Harris simulator does not have this capability. However, the tests at DICEF did not include cases involving more than one path per time delay, hence no performance difference occurs due to this difference in features.

From the foregoing discussion, it can be seen that modem performance cannot be expected to be identical on the two simulators even when the HF path parameters are set identical. Hence, the two sets of tests provide somewhat complimentary operation.

3.2.1 Test Plan

The format test plan for testing on the RADC simulator is shown in Appendix B. In Appendix C, a definitive description of the RADC simulator inputs for each test curve (channel condition) are given. Appendix D presents the run time in minutes for each data point. In some cases, the run time was longer than that shown, but in no case was it less. Appendix E lists the data rates tested under the channel conditions of each test curve.

In general, the first 10 test curves represent identical channel conditions to those reported in Paragraph 3.1. These are parametric runs and can be matched with the NTIA data as parallel tone modems which was taken by Watterson. Curves 11 through 14 represent pathological cases which match cases tested on the GTE modem. Only curves 11 and 12 at 2.4 kb/s can be compared directly with GTE results, however, since these were the only cases tested by GTE in half duplex or simplex mode. The remaining GTE tests involved a form of full duplex ARQ which is difficult to compare directly with Harris continuous half duplex operation. Curve 15 was defined during the test program to be curve 14 with periodic impulses. The periodic impulses were full scale in size and were 200 μs in width. Two conditions were run. These involved pulse rates of 60 pulses per minute and 2 pulses per minute. The latter case is more representative of conditions as they were observed in a previous link test involving an 800 mile east-west path.

It should be noted that the definition of Doppler Spread used for the DICEF HF simulator differs by a factor of two from that used by Watterson. In this report, we have used Watterson's definition. Hence, the values entered into the DICEF simulator for Doppler Spread are one-half of those reported for data run by Watterson and on the Harris simulator.

The times planned for measuring performance under each channel condition (Appendix D) were selected to depend upon both the anticipated bit error rate, to assure that a sufficient number of errors occurred, and upon the channel conditions, to assure that a sufficient number of channel fades occur. The latter is particularly important in HF simulator measurements since the errors tend to be of a burst nature corresponding to fades in the channel.

The data was taken with information bit rates of 2.4 kb/s, 3.6 kb/s, and 4.8 kb/s. The data previously taken on the Harris simulator indicates that rates of 2.4 kb/s and 4.8 kb/s were likely to yield the most interesting results. Hence, only one curve was run on the RADC simulator at 3.6 kb/s.

In addition to the normal simulator tests, three curves were run in which the AXEL Model 771 telephone line simulator was tandemed with the link simulator. The telephone simulator was set to represent either "nominal worst-case" C2 or "nominal worst-case" 3002 line conditions relative to group delay and attenuation characteristics. No other telephone disturbances were turned on in this case. The purpose of these tests was to assess the effect of telephone tail circuits that might be tandemed with the modem at large ground HF sites.

3.2.2 Test Setup

Figure 3.2.2-1 shows the test setup that was used for DICEF testing. The Harris Modem analog baseband output was fed directly to the RADC simulator. The RADC simulator analog baseband output was supplied to an analog AGC circuit to approximate the RF receive AGC. The AGC output supplied the modem input. A Hewlett-Packard 1645A error analyzer was used to simulate the data and to measure bit and block errors. The error analyzer provided a pseudonoise bit pattern to the modem modulator and compared the modem receiver output against this pattern to determine error rate. The analyzer output was supplied to a Hewlett-Packard 5150A printer which periodically printed both bit error rate and block error rate (blocks defined as 1000-bit durations). The usual setting for the printer was such that a measurement of bit error rate and block error rate were printed every 10^5 information bits. In higher error rate cases, the measurement period was reduced to 10^4 bits to avoid overflow of the error counter.

For some tests, an AXEL Model 771 telephone line simulator was tandemed with the link simulator. This is shown in Figure 3.2.2-2.

3.2.3 Test Results

The results of the tests conducted on the RADC simulator are presented as plotted curves in this section.

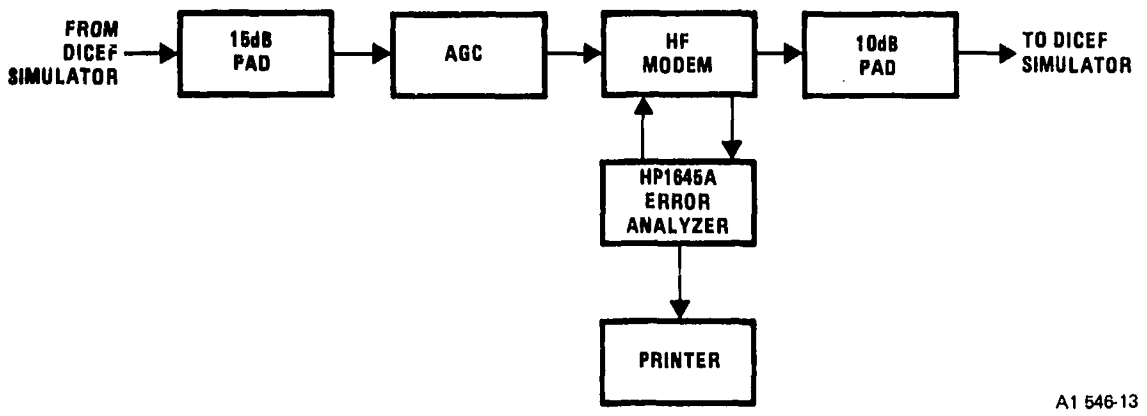

Figure 3.2.2-1. DICEF Test Setup

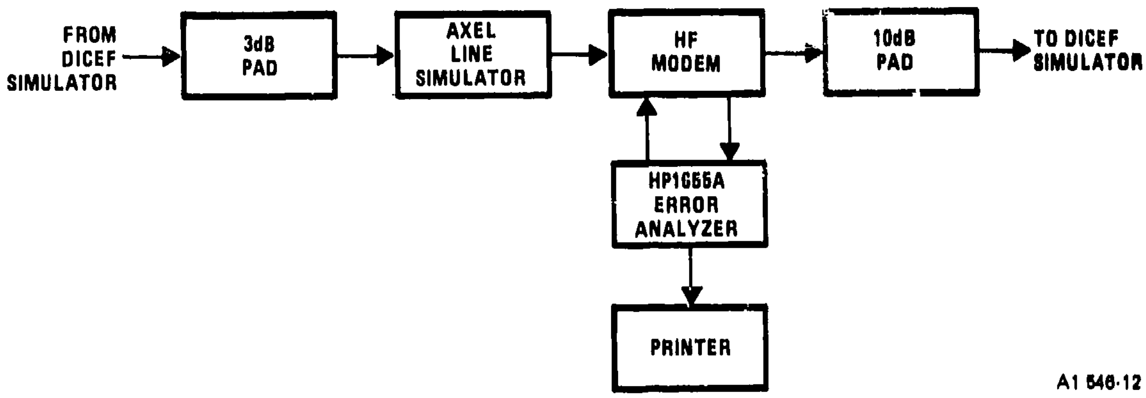

Figure 3.2.2-2. DICEF Test Setup With AXEL 771

3.2.3.1 Single Fading Path Versus E_{pb}/N_0

The data taken on the RADC simulator for the case of a single fading path with various values of peak energy per bit to noise spectral height (E_{pb}/N_0) are plotted in Figures 3.2.3.1-1, 3.2.3.1-2, and 3.2.3.1-3. In all cases, the peak energy per bit is assumed to be 1 dB higher than the average energy bit (as was the case in the Harris simulator data). Both the average bit error rate and average block error rate (based upon 1000-bit blocks) are presented for modem operation at 2.4 kb/s and 4.8 kb/s. The three curves correspond to curves 1, 2, and 3 in Appendix C and represent conditions where the Doppler Spread (by Watterson's definition) was 0.2 Hz, 1.0 Hz and 2.0 Hz, respectively.

3.2.3.2 Dual Fading Path Versus E_{pb}/N_0

The data taken for two fading paths, one delayed 1 ms relative to the other, is shown in Figures 3.2.3.2-1, 3.2.3.2-2, and 3.2.3.2-3. As in the case of the single fading path, the data is plotted versus peak energy bit/noise spectral height ratio and the three curves correspond to Doppler Spreads of 0.2 Hz, 1.0 Hz, and 2.0 Hz, respectively. The actual measured values are shown in all cases so that the interpolation involved in the curve plotting can be seen. The three curves mentioned above correspond to curves 4, 5, and 6 of Appendix C at rates of 2.4 kb/s and 4.8 kb/s. A plot of 3.6 kb/s data for curve 5 (1 Hz fade rate) is shown in Figure 3.2.3.2-4.

3.2.3.3 Single and Dual Fading Path Versus Doppler Spread

The irreducible error rates for the modem for varying Doppler Spreads are shown in Figures 3.2.3.3-1 and 3.2.3.3-2. In both cases, the value of E_{pb}/N_0 was set to infinity. In the first case, a single fading path was used. In the second, two fading paths with 1 ms differential delay were present. In this case, both paths varied at the Doppler Spread rate shown. These correspond to curves 7 and 8 of Appendix C.

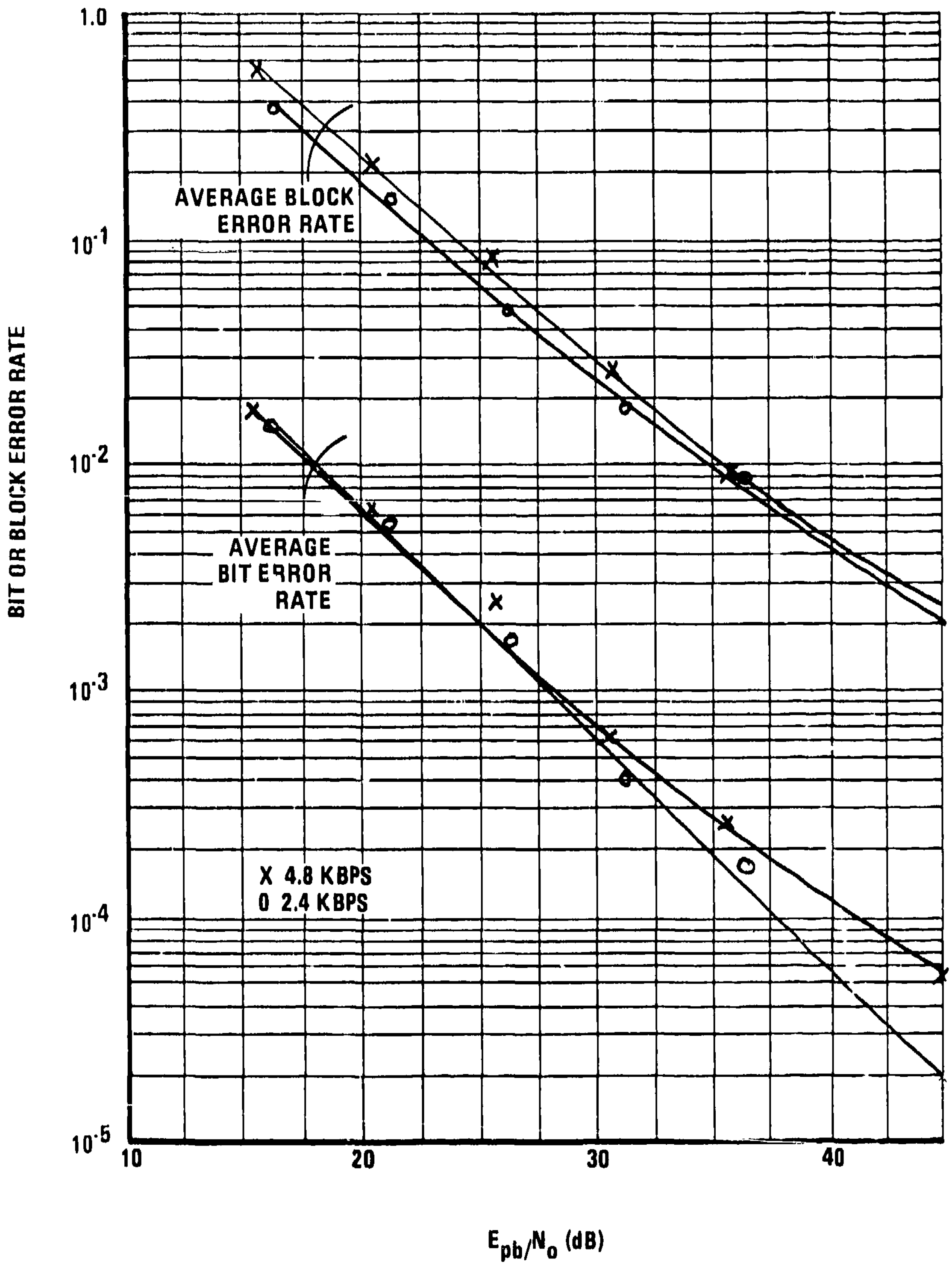

Figure 3.2.3.1-1. Single Fading Path With 0.2 Hz Doppler Spread

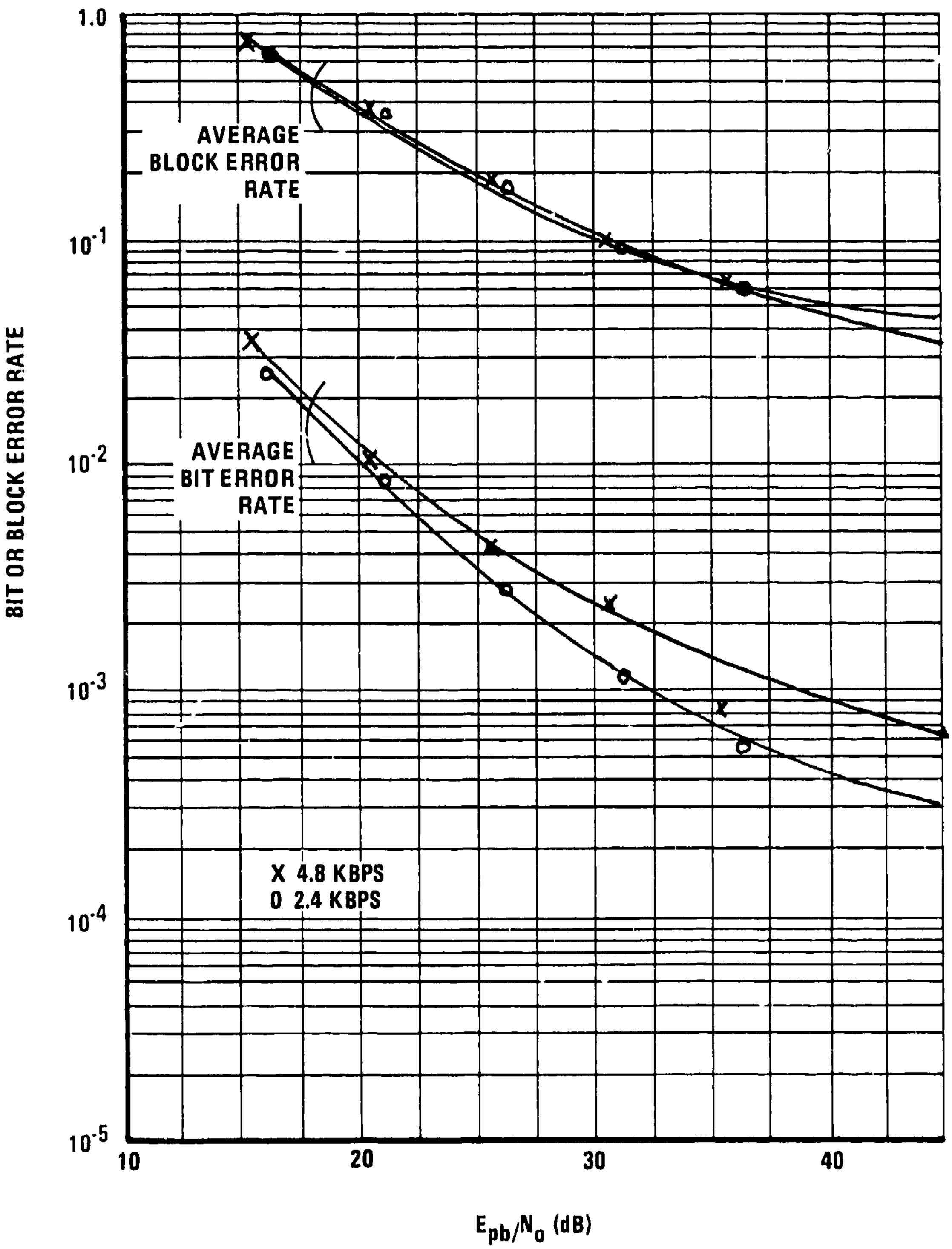

Figure 3.2.3.1-2. Single Fading Path With 1.0 Hz Doppler Spread

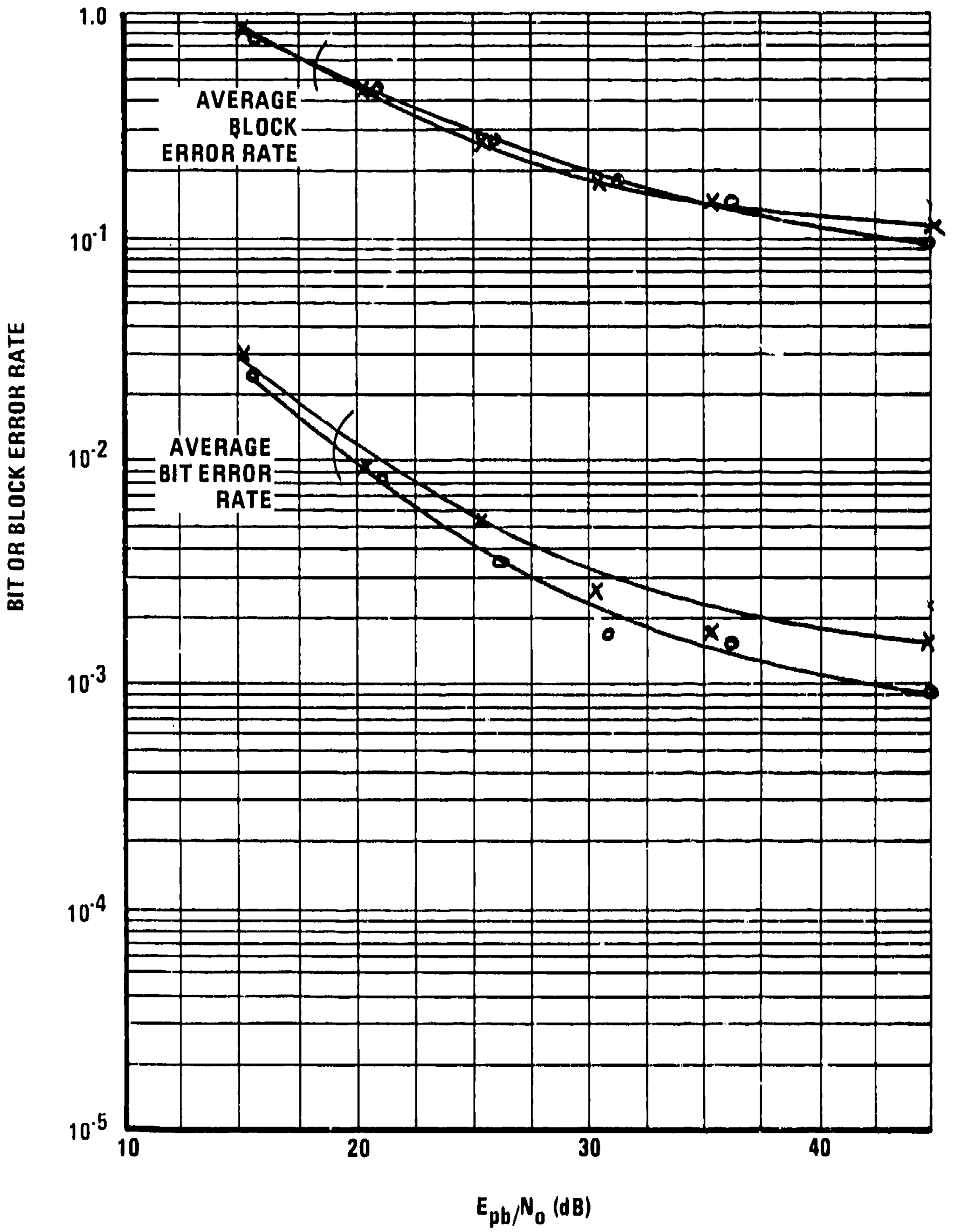

Figure 3.2.3.1-3. Single Fading Path With 2.0 Hz Doppler Spread

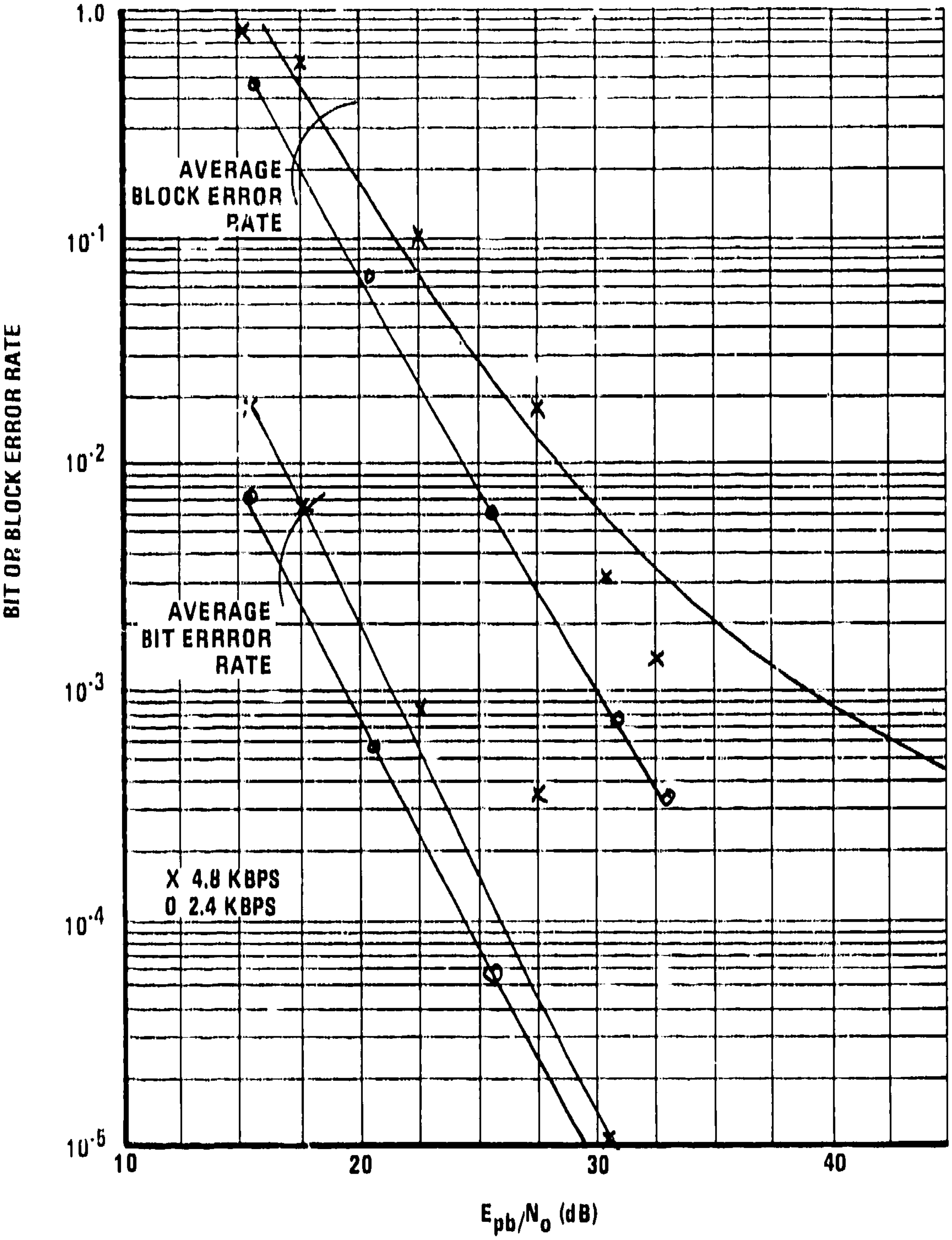

Figure 3.2.3.2-1. Dual Fading Path With 1 ms Relative Delay and 0.2 Hz Doppler Spread

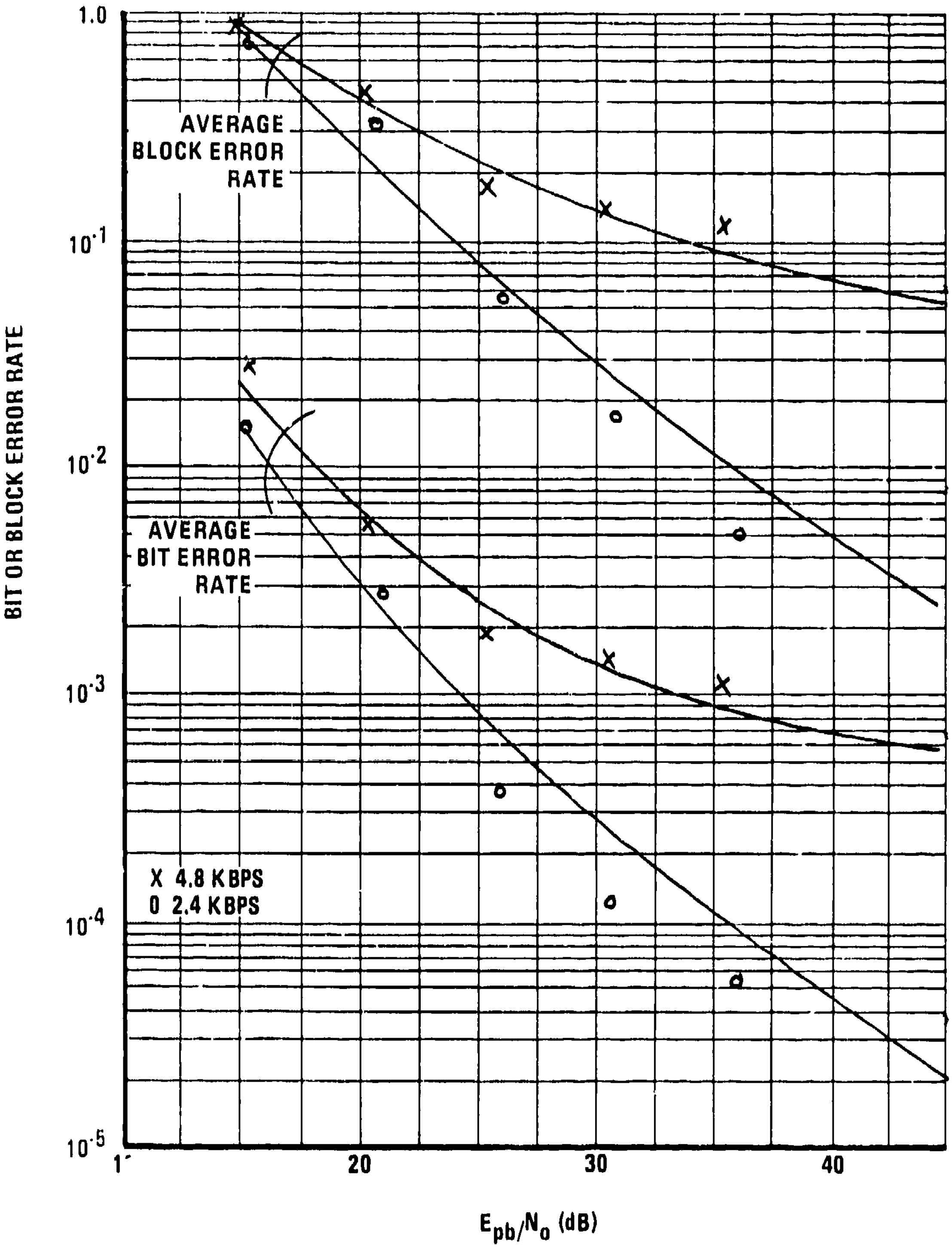

Figure 3.2.3.2-2. Dual Fading Path With 1 ms Relative Delay and 1.0 Hz Doppler Spread

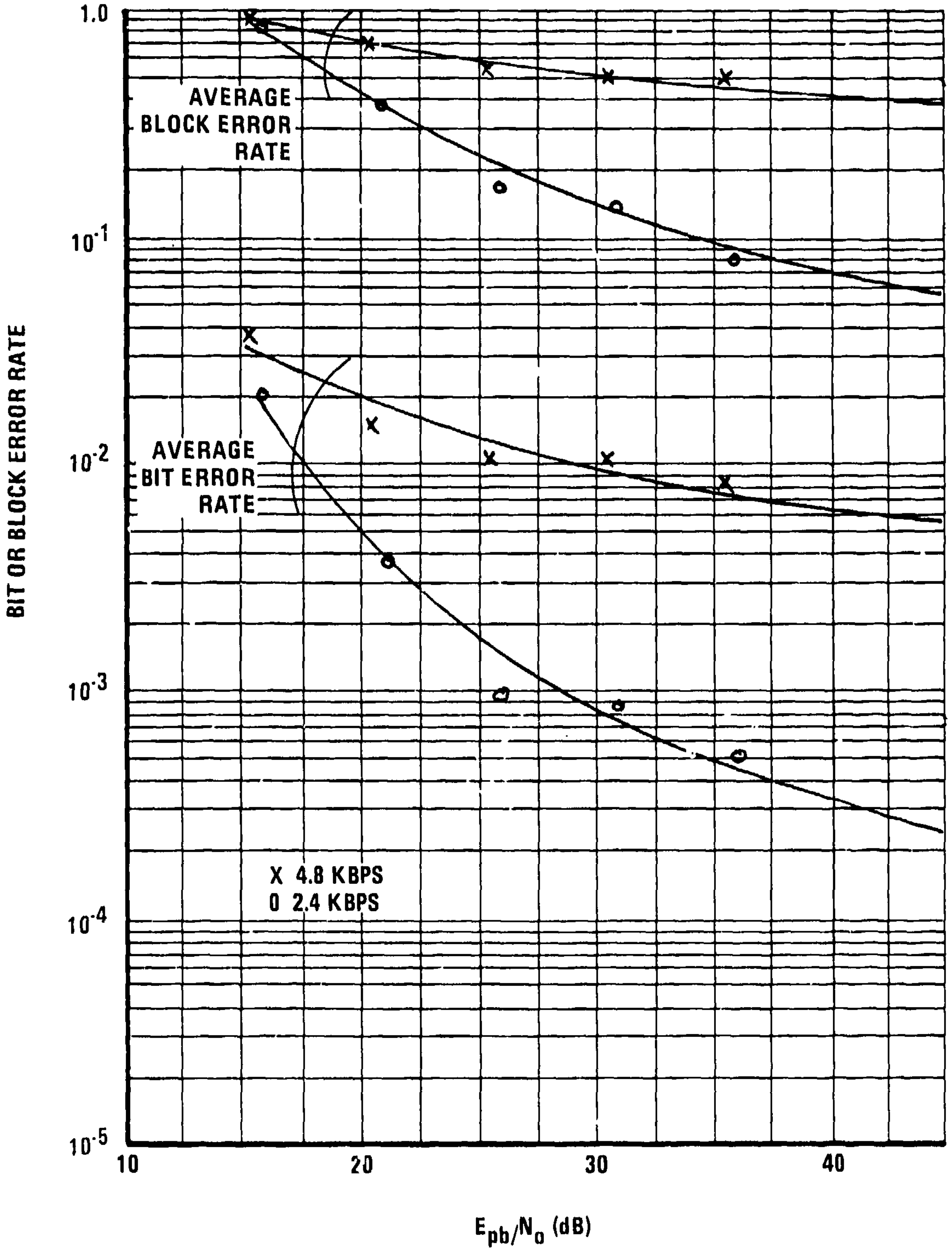

Figure 3.2.3.2-3. Dual Fading Path With 1 ms Relative Delay and 2.0 Hz Doppler Spread

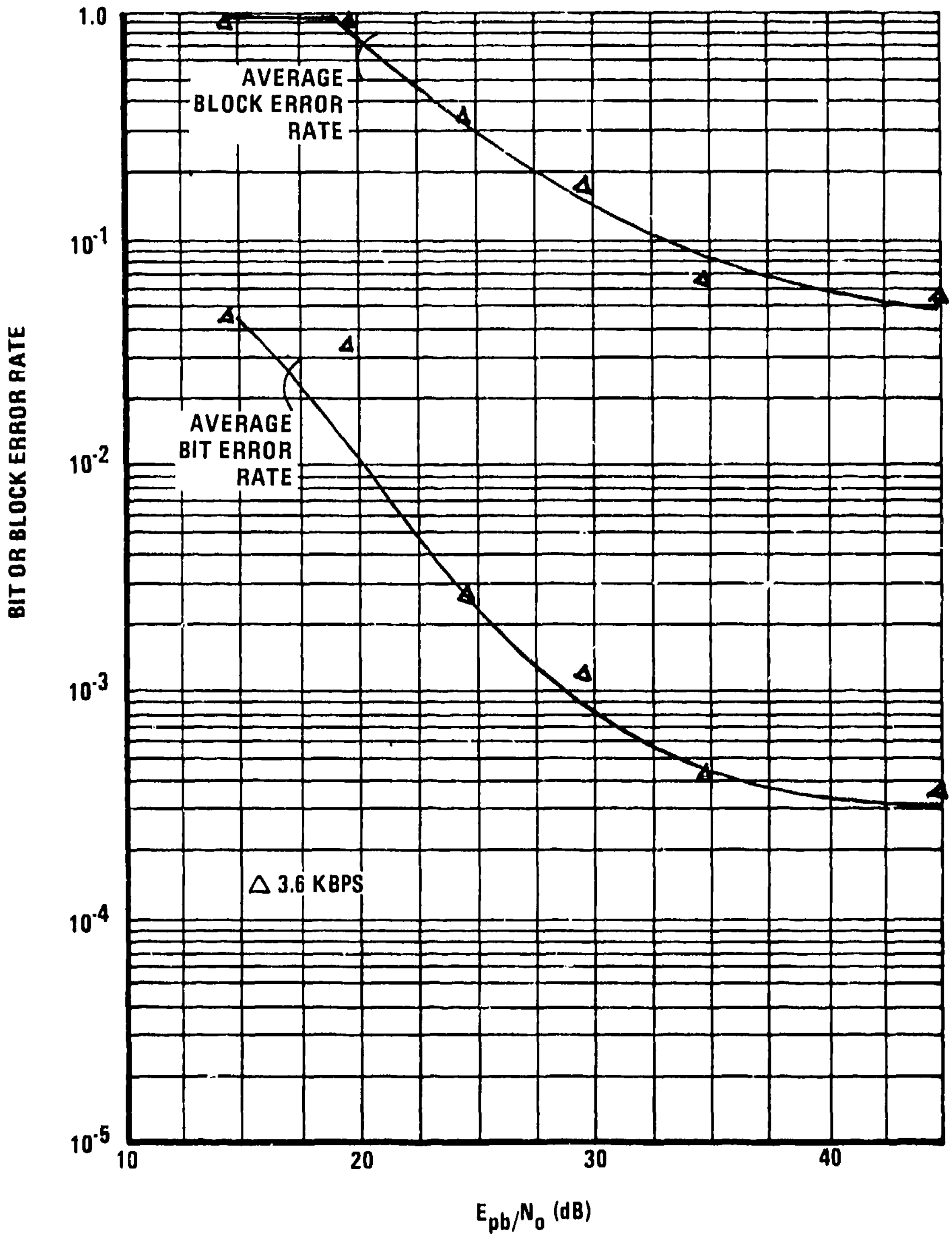

Figure 3.2.3.2-4. Dual Fading Path With 1 ms Relative Delay and 1.0 Hz Doppler Spread at 3.6 kb/s

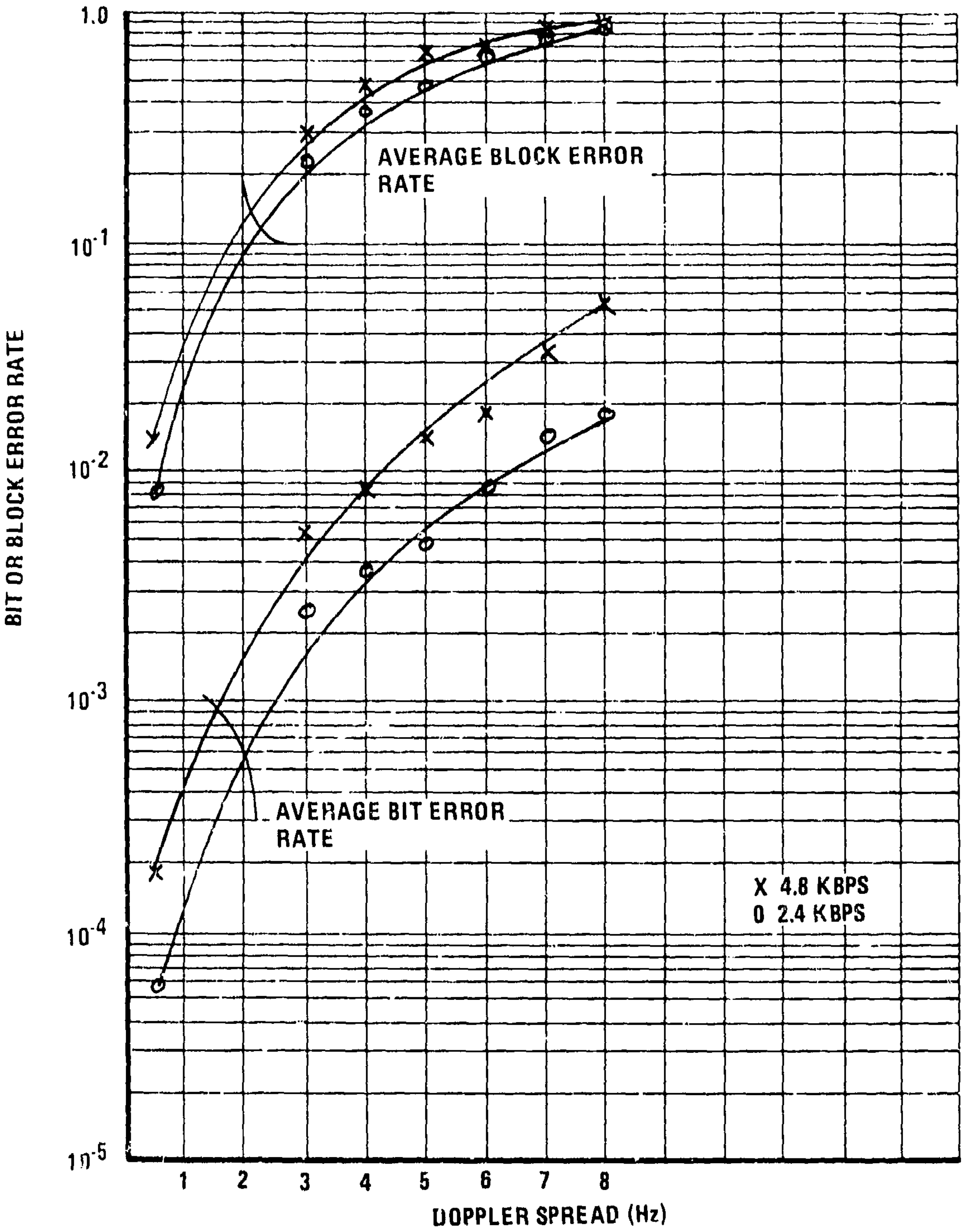

Figure 3.2.3.3-1. Single Fading Path With $E_{pb}/N_o = \infty$

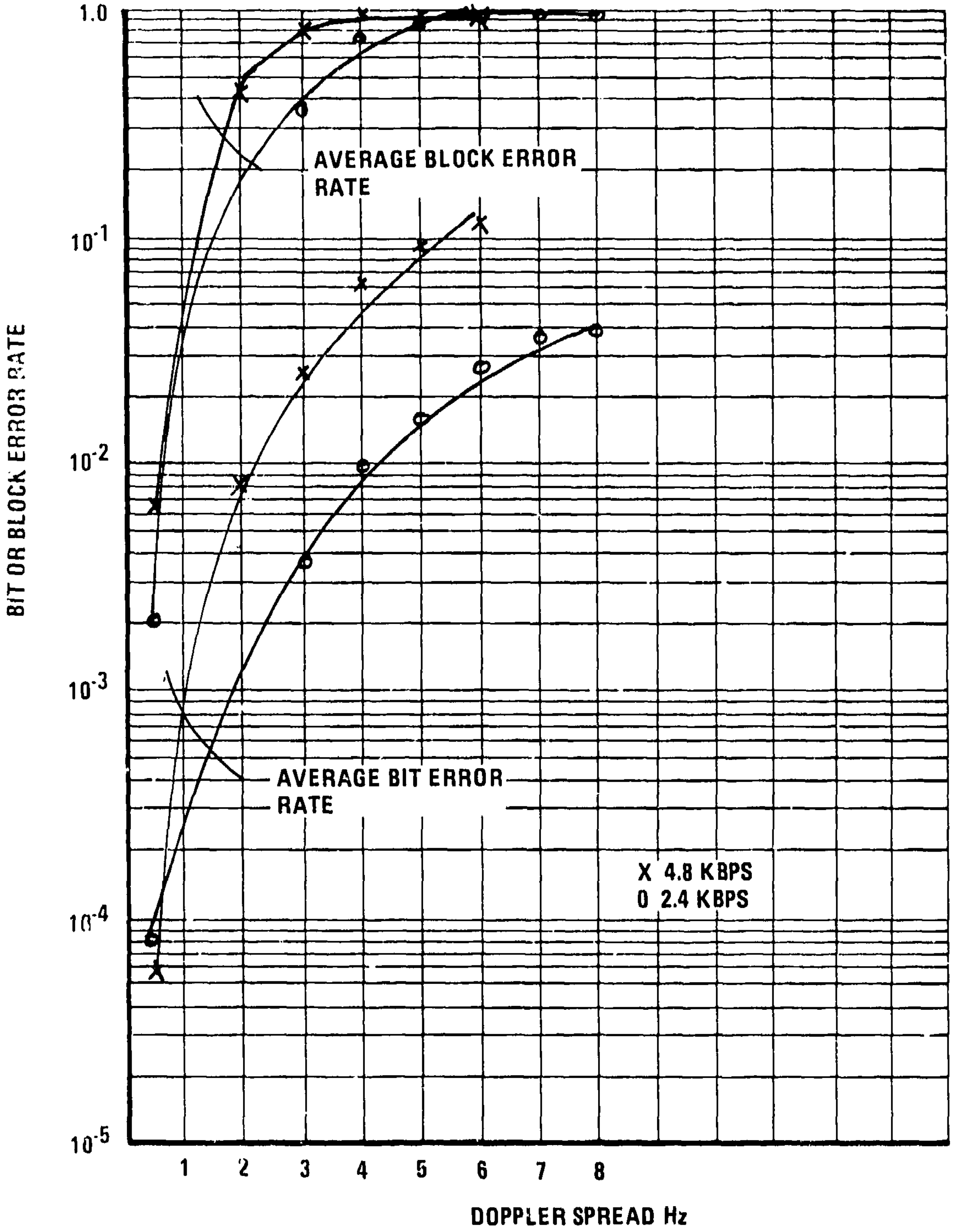

Figure 3.2.3.3-2. Single Fading Path With 1 ms Relative Delay and $E_{pb}/N_o = \infty$

3.2.3.4 Dual Fading Path Versus Differential Delay

In Figure 3.2.3.4, the performance for the case of dual fading paths with different delay spreads is shown. Both paths had a Doppler spread of 1 Hz and the value of E_{pb}/N_0 were infinite. This corresponds to curve 9 of Appendix C.

3.2.3.5 Dual Fading Path Versus Differential Doppler

In Figure 3.2.3.5, the performance is shown in the case of two fading paths with a differential time delay of 1 ms and each with a Doppler Spread of 1 Hz. In this case, the first path has an average Doppler Spread of zero and the second has an average Doppler rate as shown. It should be noted that all of the previous curves have been run with an average Doppler rate of zero for all paths. This corresponds to curve 10 of Appendix C.

3.2.3.6 Performance for Pathological Channels Versus E_{pb}/N_0

The modem performance was measured for four different pathological cases corresponding to conditions specified in curves 11, 12, 13, and 14 of Appendix C. The results are plotted against E_{pb}/N_0 in Figures 3.2.3.6-1 through 3.2.3.6-4. In figure 3.2.3.6-1, the conditions were such that dual fading paths were present. The first of these had no time delay, had an average Doppler rate of -0.5 Hz, and had a Doppler Spread of 0.05 Hz. The amplitude of this path was -16 dBm. The second path, delayed by 1.2 ms, had an average Doppler rate of +0.5 Hz, a Doppler Spread of 0.05 Hz, and an amplitude of 0 dBm. Figure 3.2.3.6-2 presents the case of two paths with 1 ms differential delay each, fading with a 0.4 Hz Doppler Spread and no average Doppler rate.

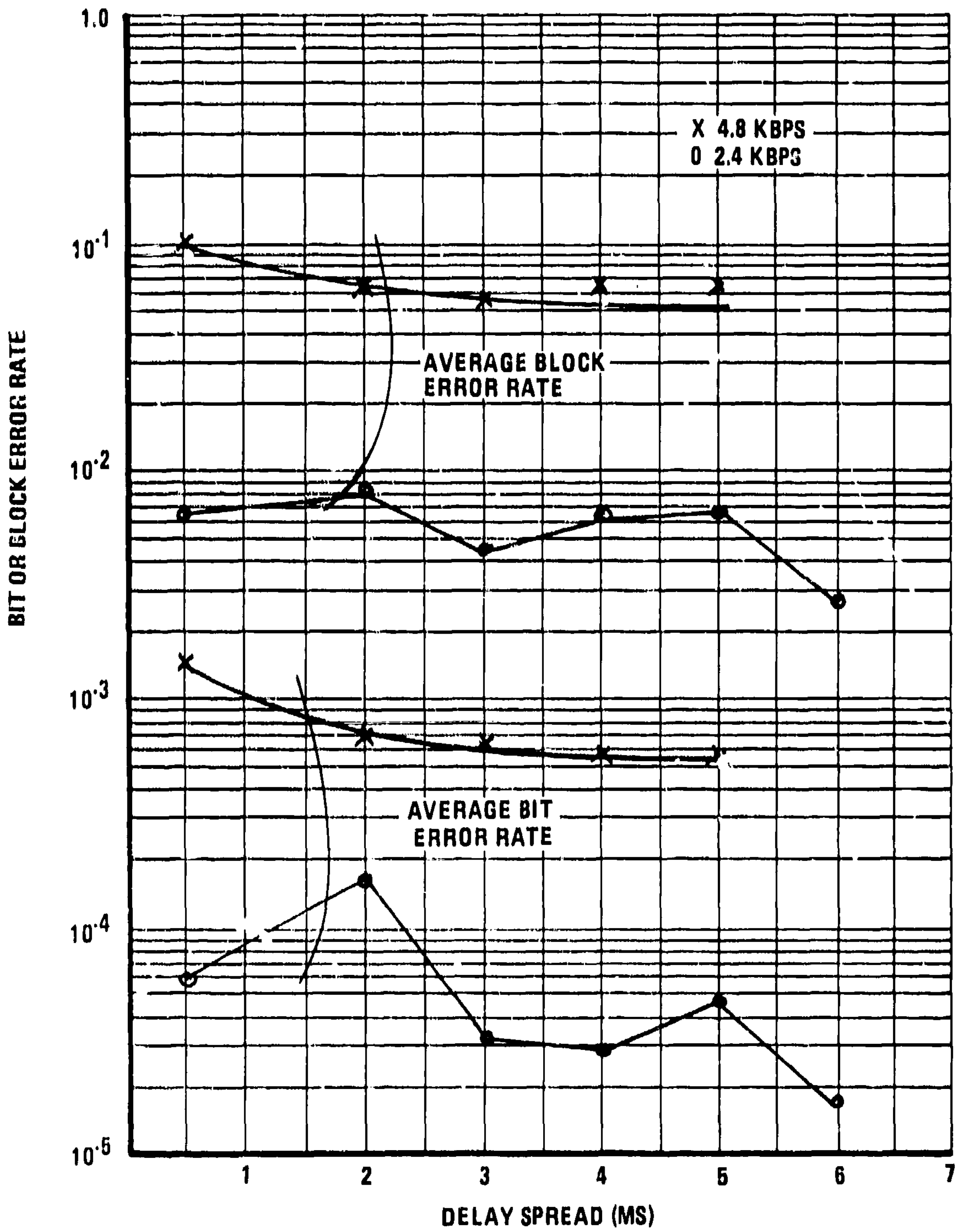

Figure 3.2.3.4. Dual Fading Path With 1.0 Hz Doppler Spread and $E_{pb}/N_0 = \infty$

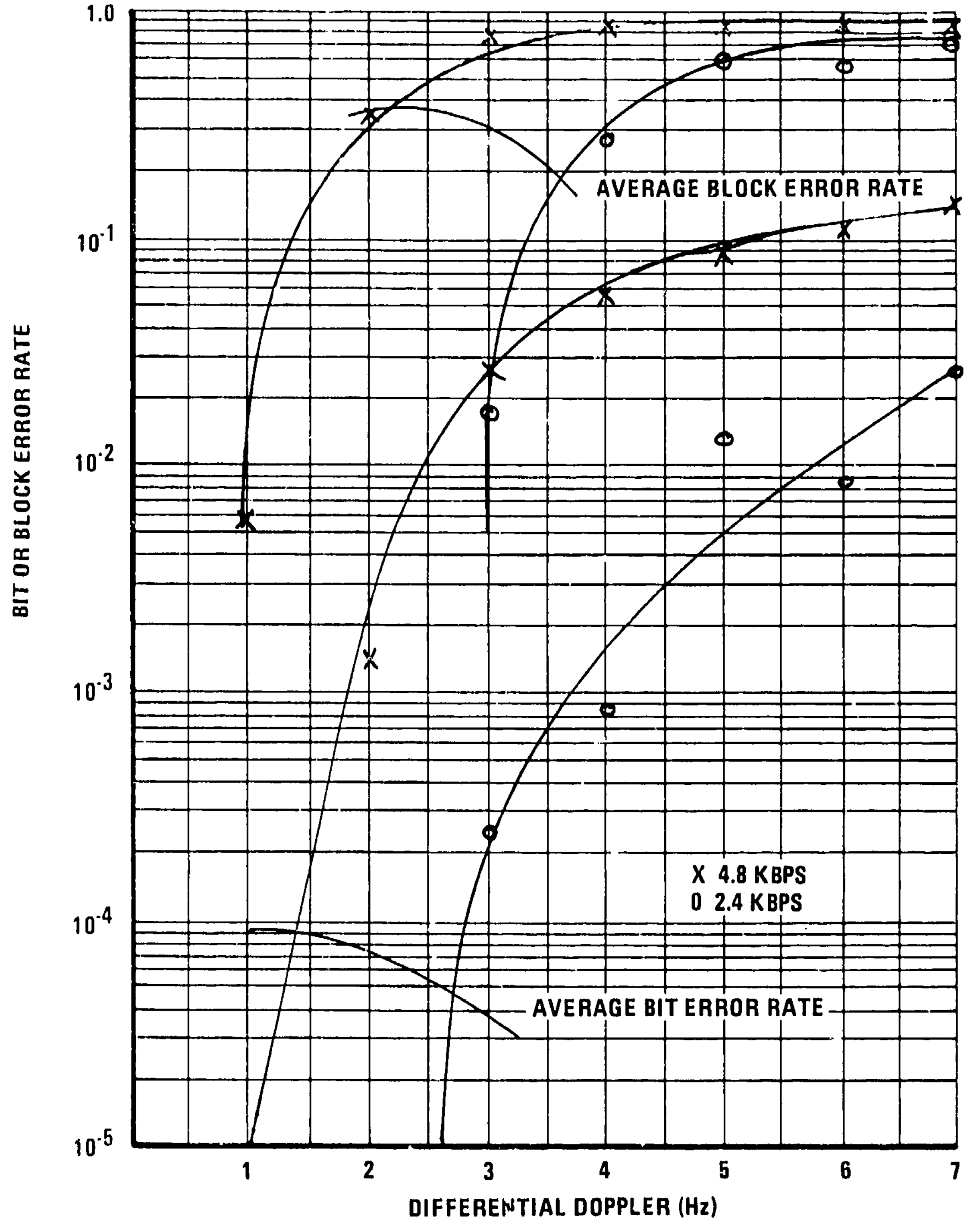

Figure 3.2.3.5. Dual Fading Path With 1 ms Relative Delay, 1 Hz Doppler Spread and $E_{pb}/N_0 = \infty$

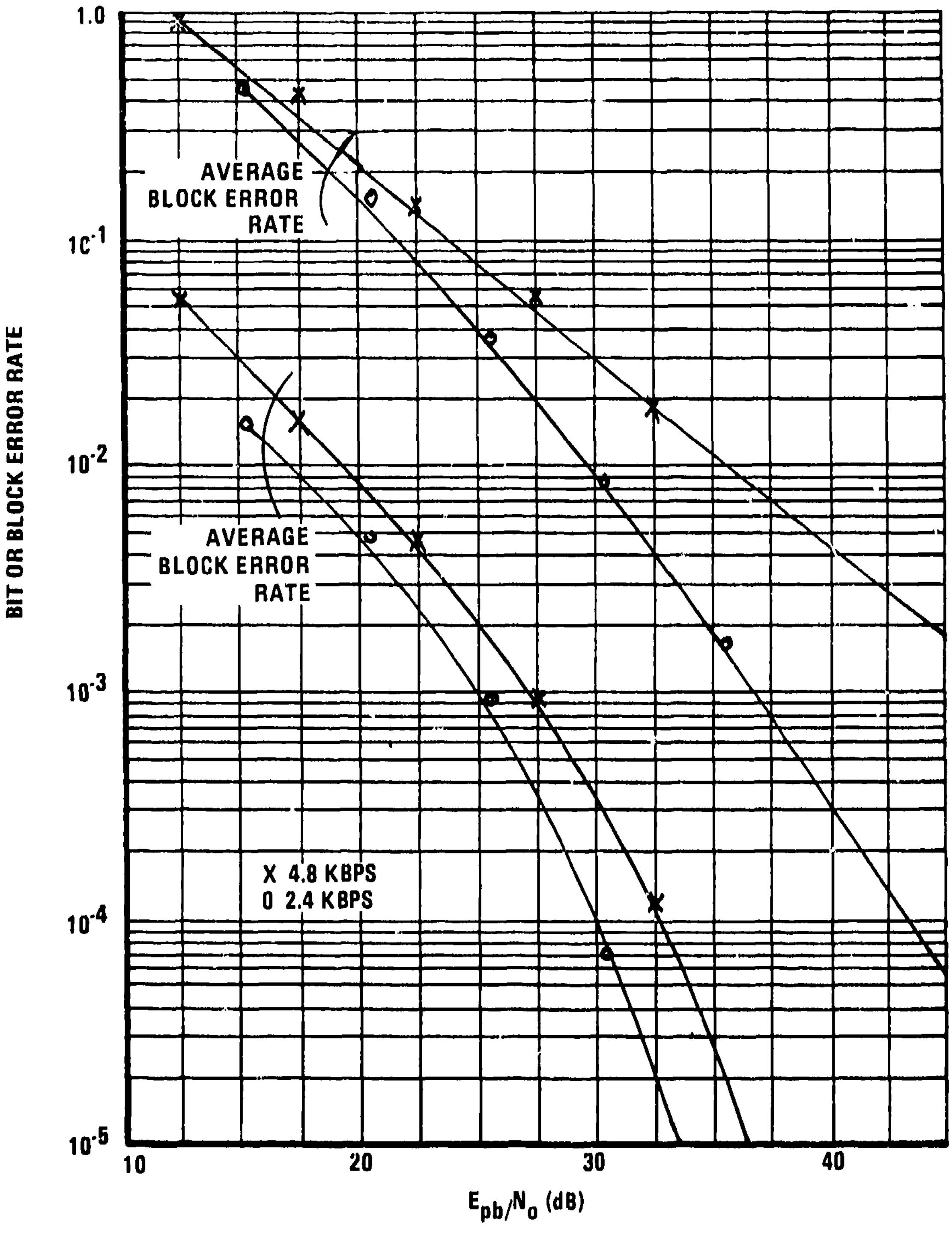

Figure 3.2.3.6-1. Dual Unbalanced Fading Path 1

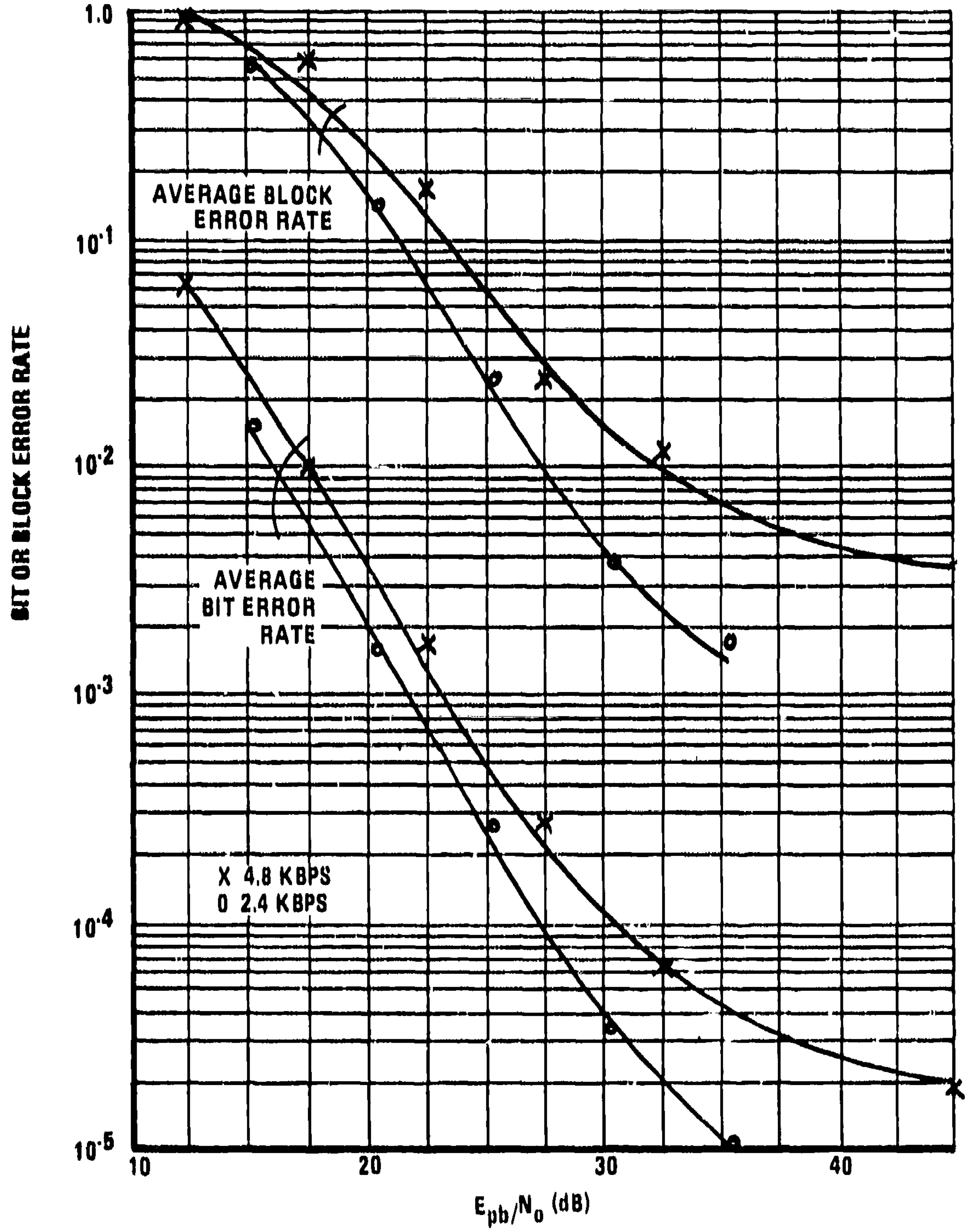

Figure 3.2.3.6-2. Dual Unbalanced Fading Path 2

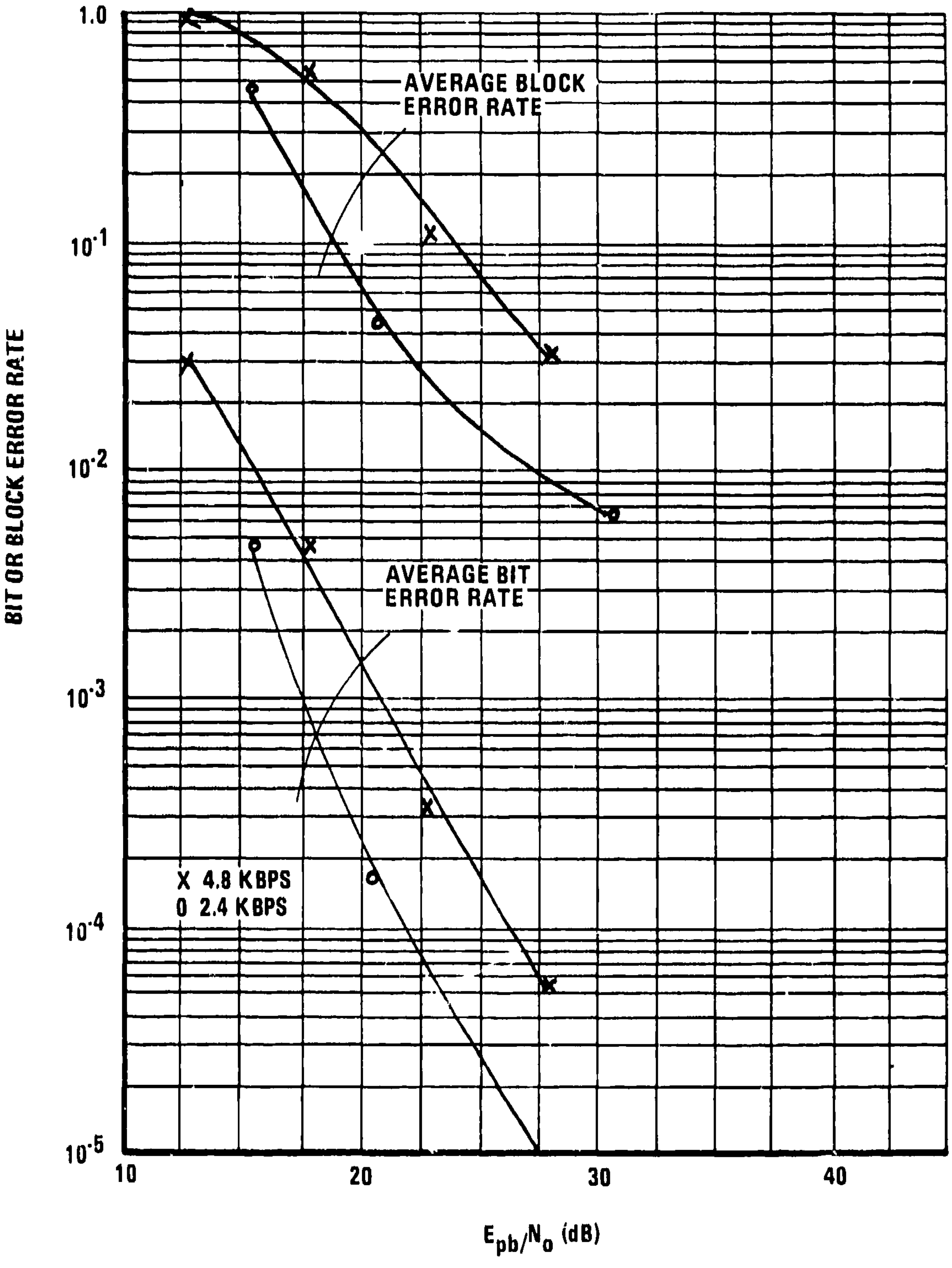

Figure 3.2.3.6-3. Triple Unbalanced Fading Path 1

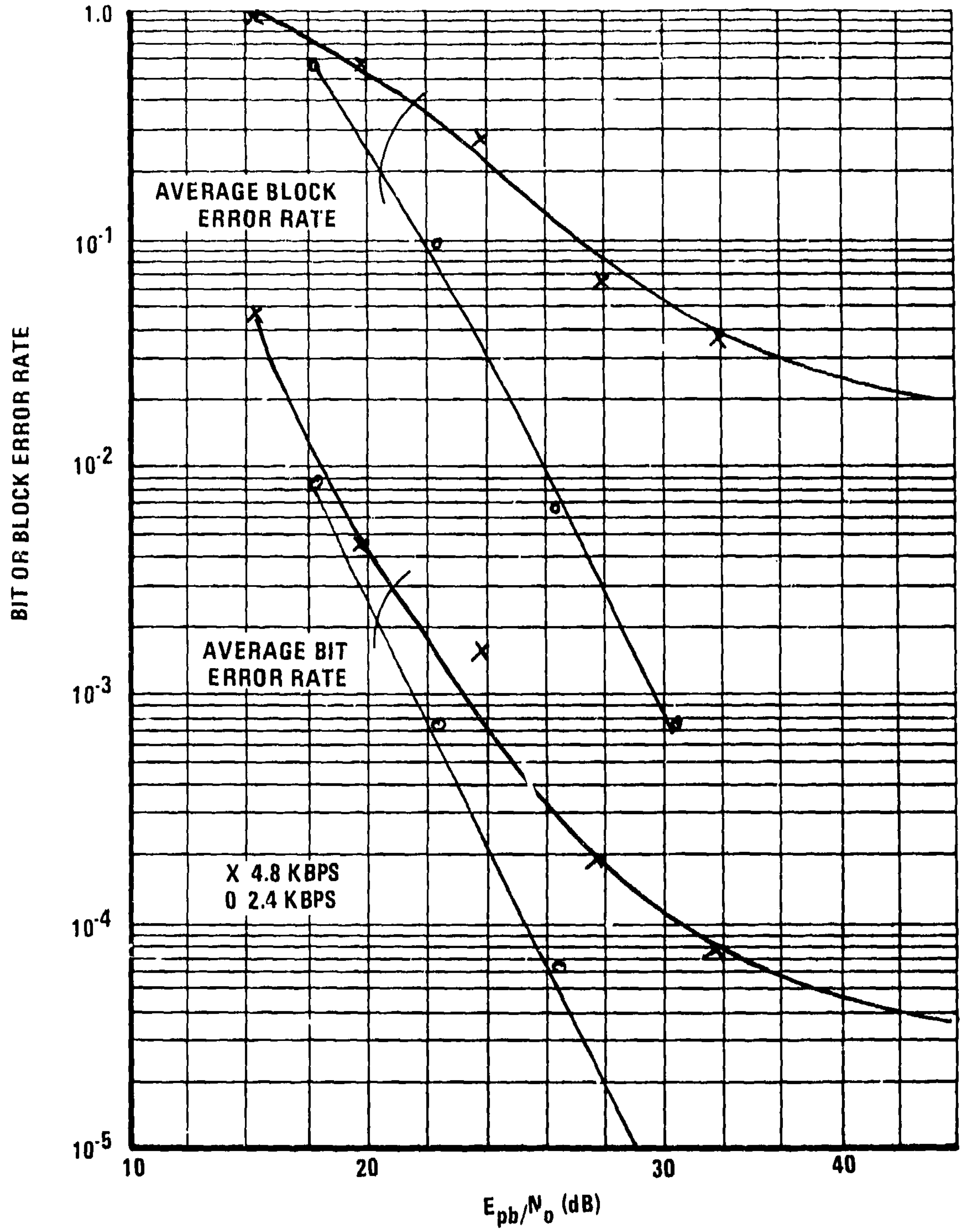

Figure 3.2.3.6-4. Triple Fading Path 2

Figure 3.2.3.6-3 presents a case in which three paths are present. These characteristics are tabulated below:

Path	Delay (Ms)	Average Doppler (Hz)	Doppler Spread (Hz)	Amp (dBm)
1	0	-0.5	0.1	-26
2	0.6	0	0.1	-12
3	2.8	+0.5	0.1	-14

In Figure 3.2.3.6-4, a different three path model was used and the path characteristics were:

Path	Delay (Ms)	Average Doppler (Hz)	Doppler Spread (Hz)	Amp (dBm)
1	0	-1	0.2	-14
2	0.6	0	0.2	0
3	2.8	1	0.2	

3.2.3.7 Performance with Impulsive Noise

Figures 3.2.3.7-1 and 3.2.3.7-2 present the performance of the modem when the pathological cases for curve 14 of Appendix C was present and periodic impulses of 200 μs in width and full scale in height were present. In Figure 3.2.3.7-1, these impulses were inserted at the rate of two per minute and in Figure 3.2.3.7-2, they were inserted at 60 per minute. As was the case of Figure 3.2.3.7-2, the curves are plotted versus E_{pb}/N_0 of the additive Gaussian noise, also present in the channel mode. These curves satisfy the requirements of curve 15 in Appendix C.

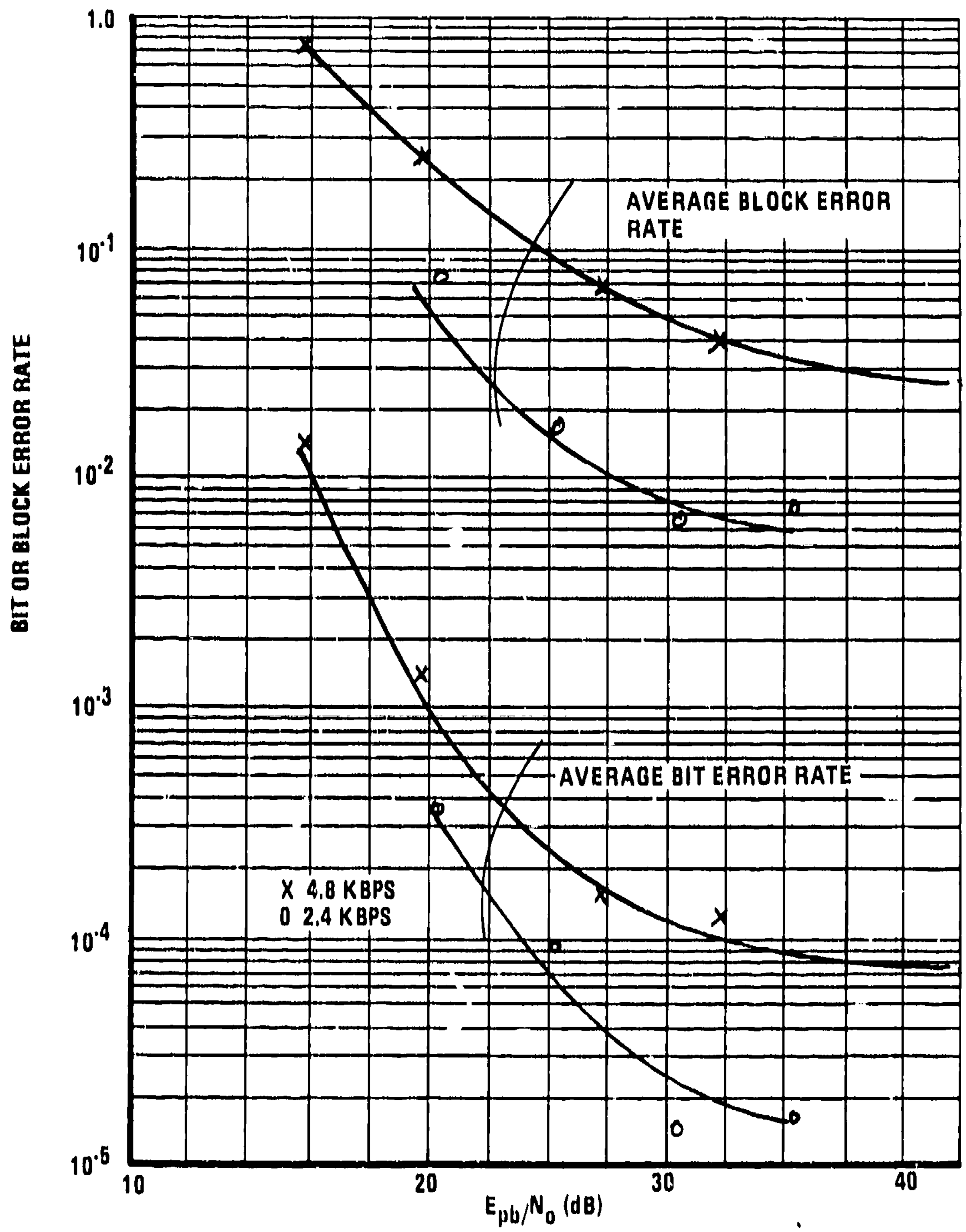

Figure 3.2.3.7-1. Triple Fading Path 2 With
Two Noise Pulses Per Minute

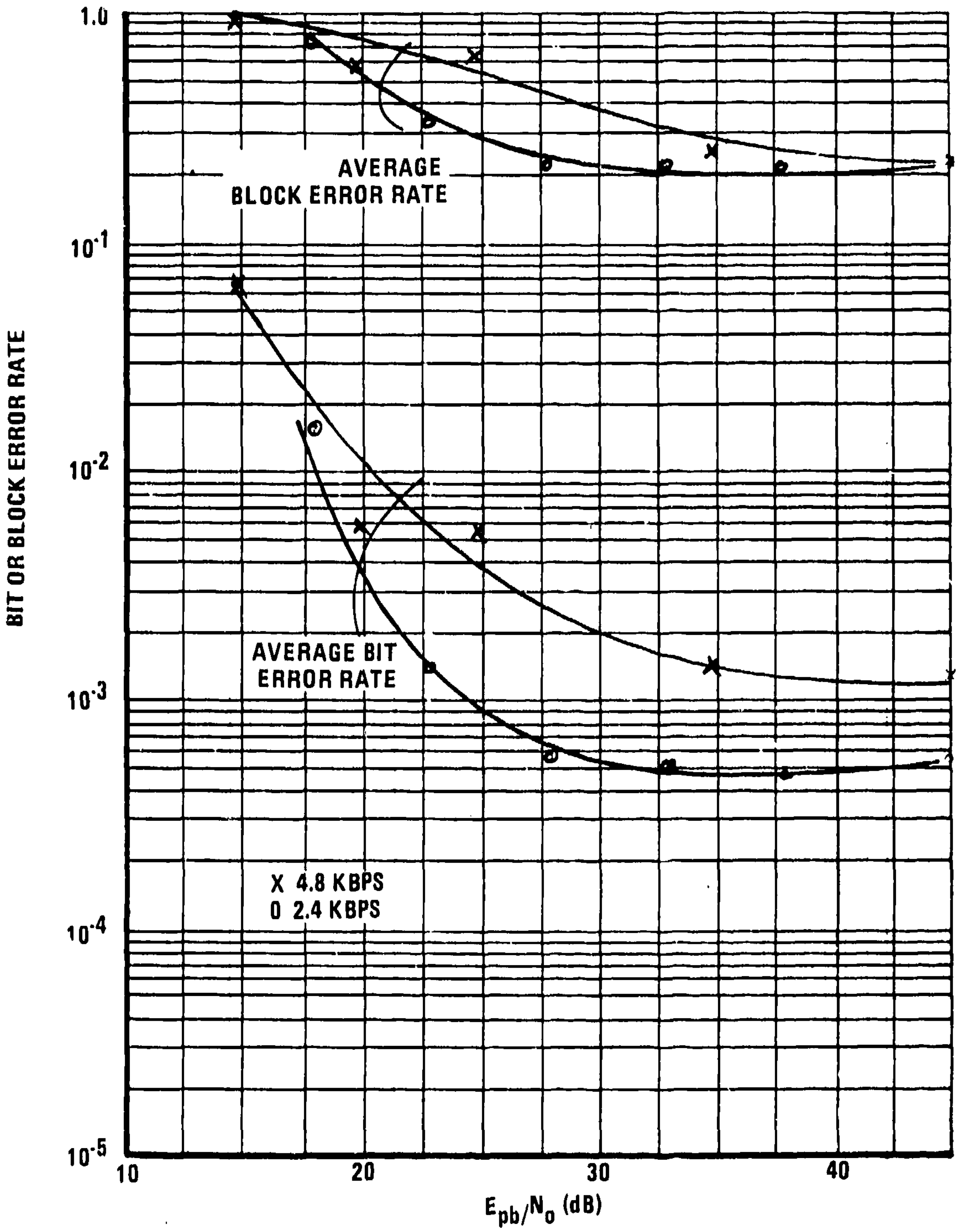

Figure 3.2.3.7-2. Triple Fading Path 2 With 60 Noise Pulses Per Minute

3.2.3.8 Performance with Telephone Simulator in Tandem

Figure 3.2.3.8 shows the performance of the modem for dual fading paths each with a Doppler Spread of 1 Hz (curve 5 of Appendix C) when a telephone simulator is placed in tandem with the link simulator. The curves shown are for 2.4 kb/s and 4.8 kb/s performance with the telephone simulator set to a C2 line conditioning and 2.4 kb/s performance with a 3002 setting of the telephone simulator. In both cases, no other disturbances were included in the telephone simulator.

3.3 Near Real-Time Simulator Tests for a 6 kHz Channel

Tests using the near real-time internal HF channel simulator were performed for the 8 kb/s mode in accordance with the test plan outlined in Appendix A. A modified set of these tests were performed for the 16 kb/s mode, as will be discussed later in this section.

These results represent the performance available on a simplex link without the capability of resynchronization. There was never an incident during the gathering of the data presented here in which the Harris Modem required resynchronization after the initial synchronization was successful. It should be noted that the modem can be operated in a push-to-talk simplex communication application without resynchronization on each turn-around, the "off" periods acting as extended deep fades.

The block error rate performance represents the fraction of 1000-bit blocks with one or more errors in them, and may be used to predict the throughput of a near error-free ARQ arrangement once the ARQ protocols are established.

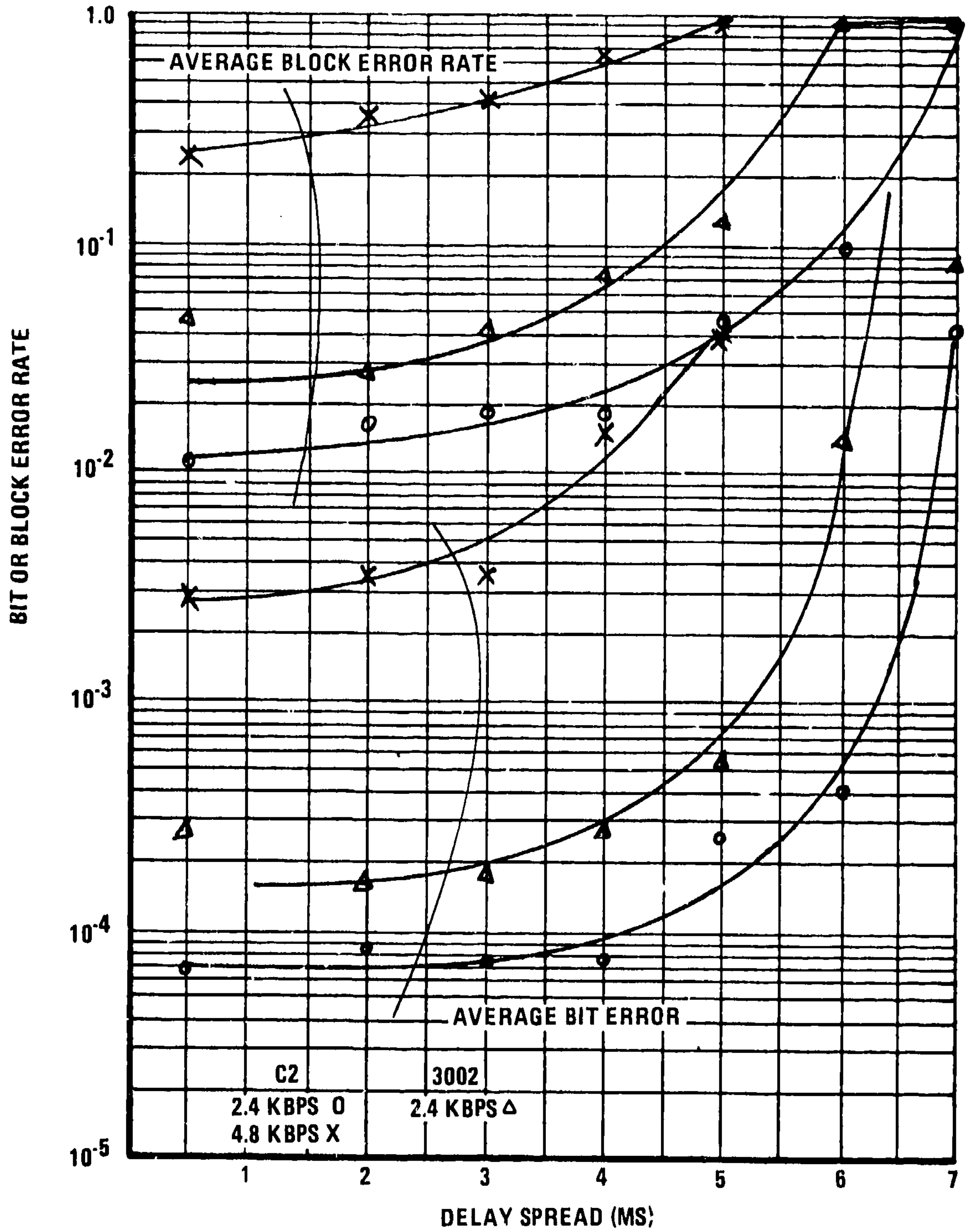

Figure 3.2.3.8. Dual Fading Paths With Doppler Spread of 1 Hz With AXEL Telephone Simulator in Tandem With DICEF HF Simulator

3.3.1 Performance of 8 kb/s in a 6 Hz Bandwidth

Figures 3.3.1-1, 3.3.1-2, and 3.3.1-3 show the performance of the 8 kb/s mode for a single fading path versus E_{pb}/N_o for Doppler Spreads of 0.2 Hz, 1.0 Hz, and 2.0 Hz, respectively. Figure 3.3.1-4 shows the irreducible error performance ($E_{pb}/N_o = \infty$) of the modem versus Doppler spread in Hz.

Figures 3.3.1-5, 3.3.1-6, and 3.3.1-7 show the performance of the 8 kb/s mode for two equal (mean) power fading paths with 1 ms relative delay (multipath spread) versus E_{pb}/N_o at Doppler Spreads of 0.2 Hz, 1.0 Hz, and 2.0 Hz, respectively. Figure 3.3.1-8 shows the irreducible error performance ($E_{pb}/N_o = \infty$) of the modem versus Doppler Spread for this two-path HF channel. Figure 3.3.1-9 shows the irreducible error performance of the modem versus the multipath spread of two equal (mean) power fading paths, each with a 1 Hz Doppler Spread. Figure 3.3.1-10 shows the irreducible error performance of the modem versus the difference in the mean Doppler frequency of two equal (mean) power fading paths with a Doppler Spread of 1 Hz and multipath spread of 1 ms.

3.3.2 Performance of 16 kb/s in a 6 Hz Bandwidth

For the 16 kb/s mode, only the performance as a funcion of signal-to-noise ratio for 0.2 Hz (Doppler Spread) fading single and dual paths was measured. Since the bit and block error rates were relatively high in the 16 kb/s mode, even for this slow fade rate, characterization of the performance at higher fade rates did not appear to be particularly useful. Some of the poor 16 kb/s performance is likely due to quantizing noise and underflow and overflow introduced by the digital implementation of the 10-pole Tschebycheff filters. This type of degradation caused by the receive filter should be greater than that caused by the transmit filter due to the more widely varying input level.

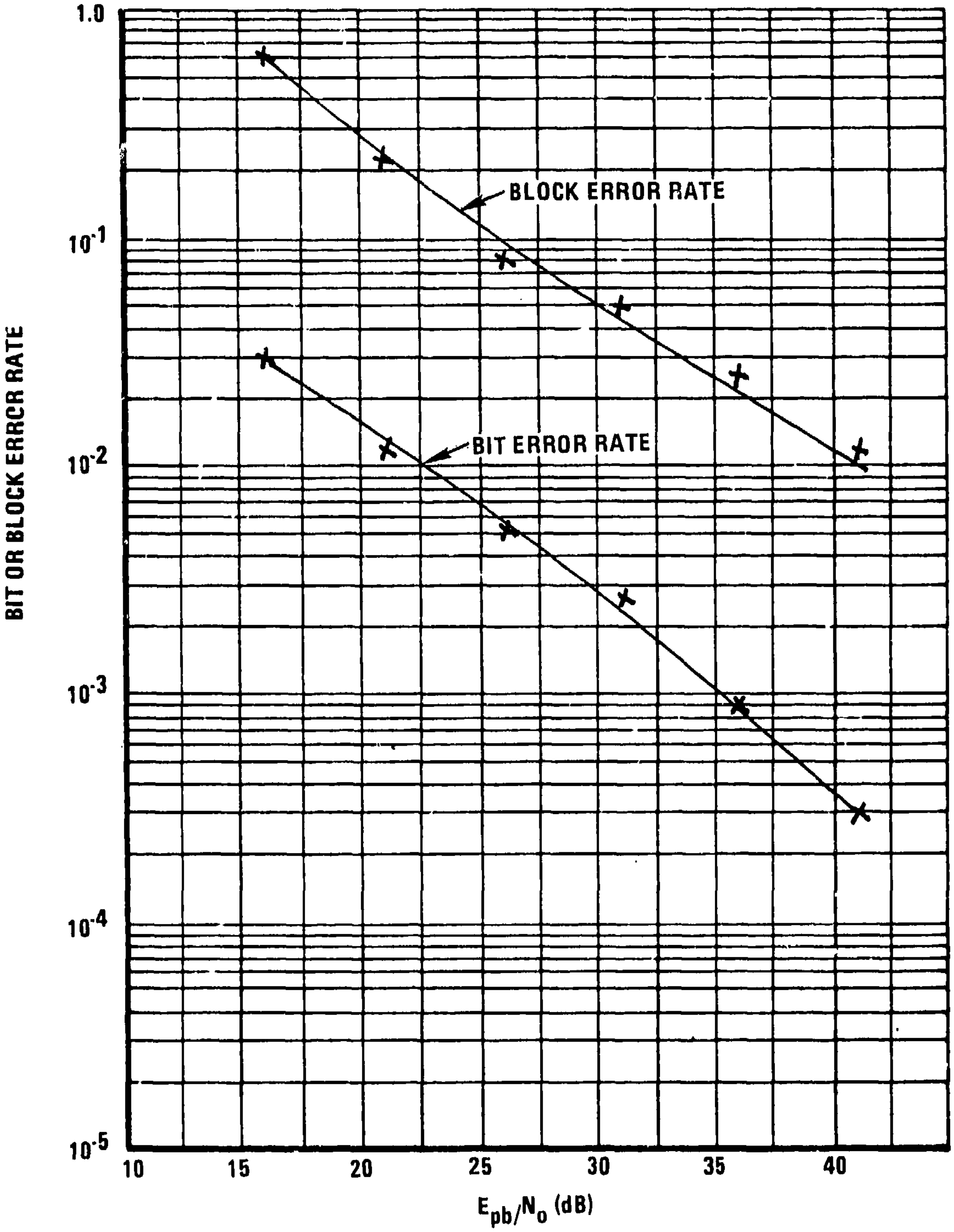

Figure 3.3.1-1. Single Fading Path With 0.2 Hz Doppler Spread at 8 kb/s

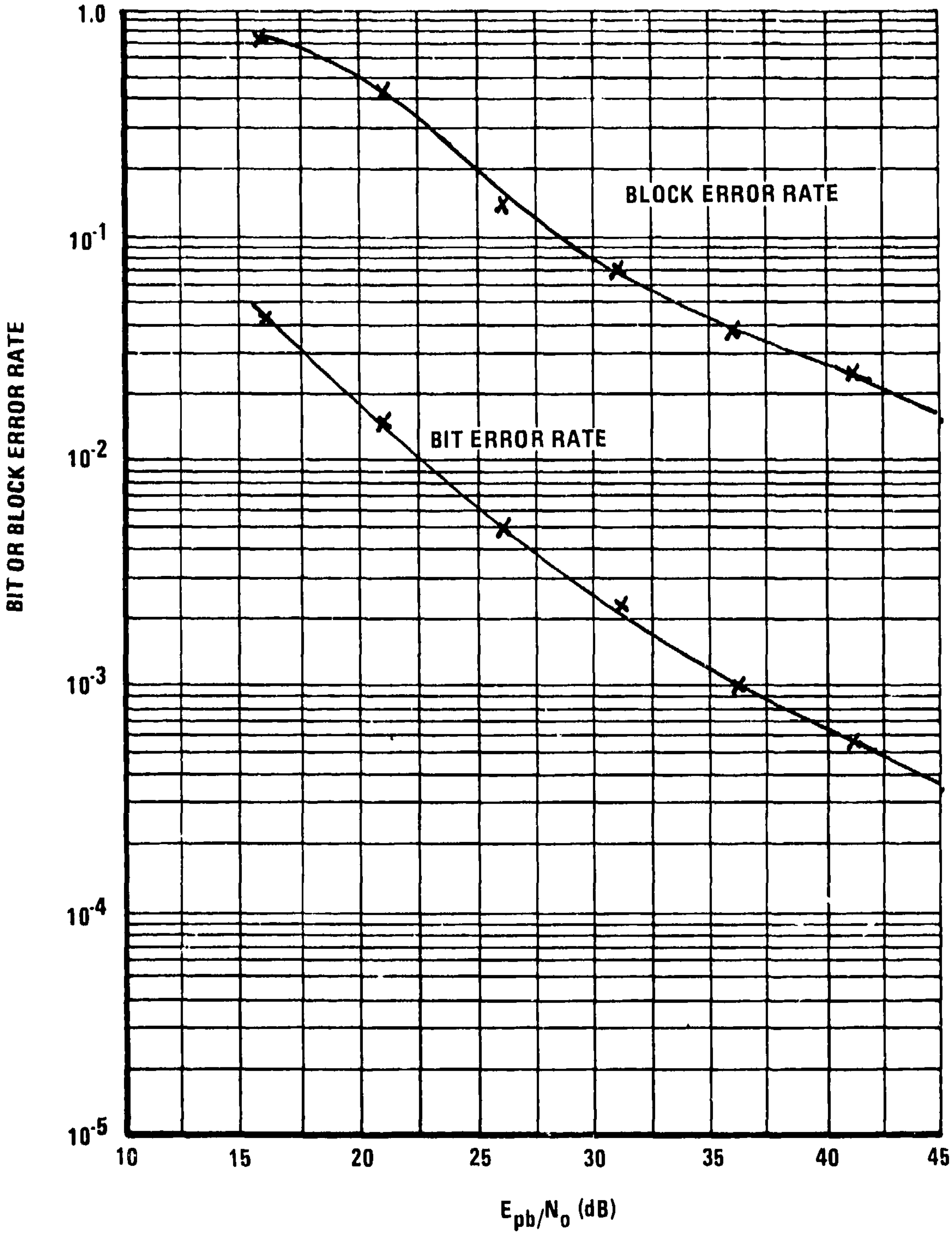

Figure 3.3.1-2. Single Fading Path With 1.0 Hz Doppler Spread at 8 kb/s

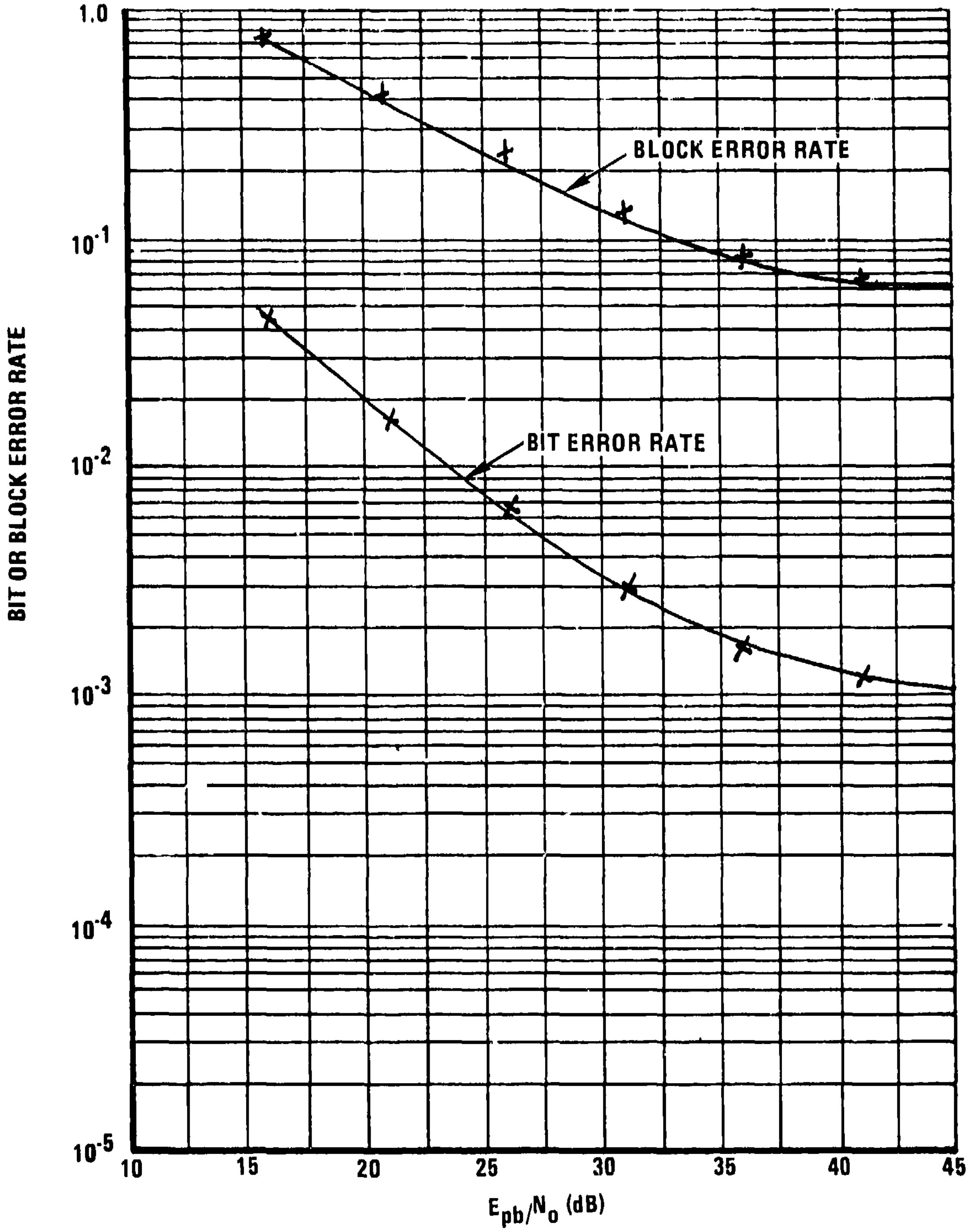

Figure 3.3.1-3. Single Fading Path With 2.0 Hz Doppler Spreaa at 8 kb/s

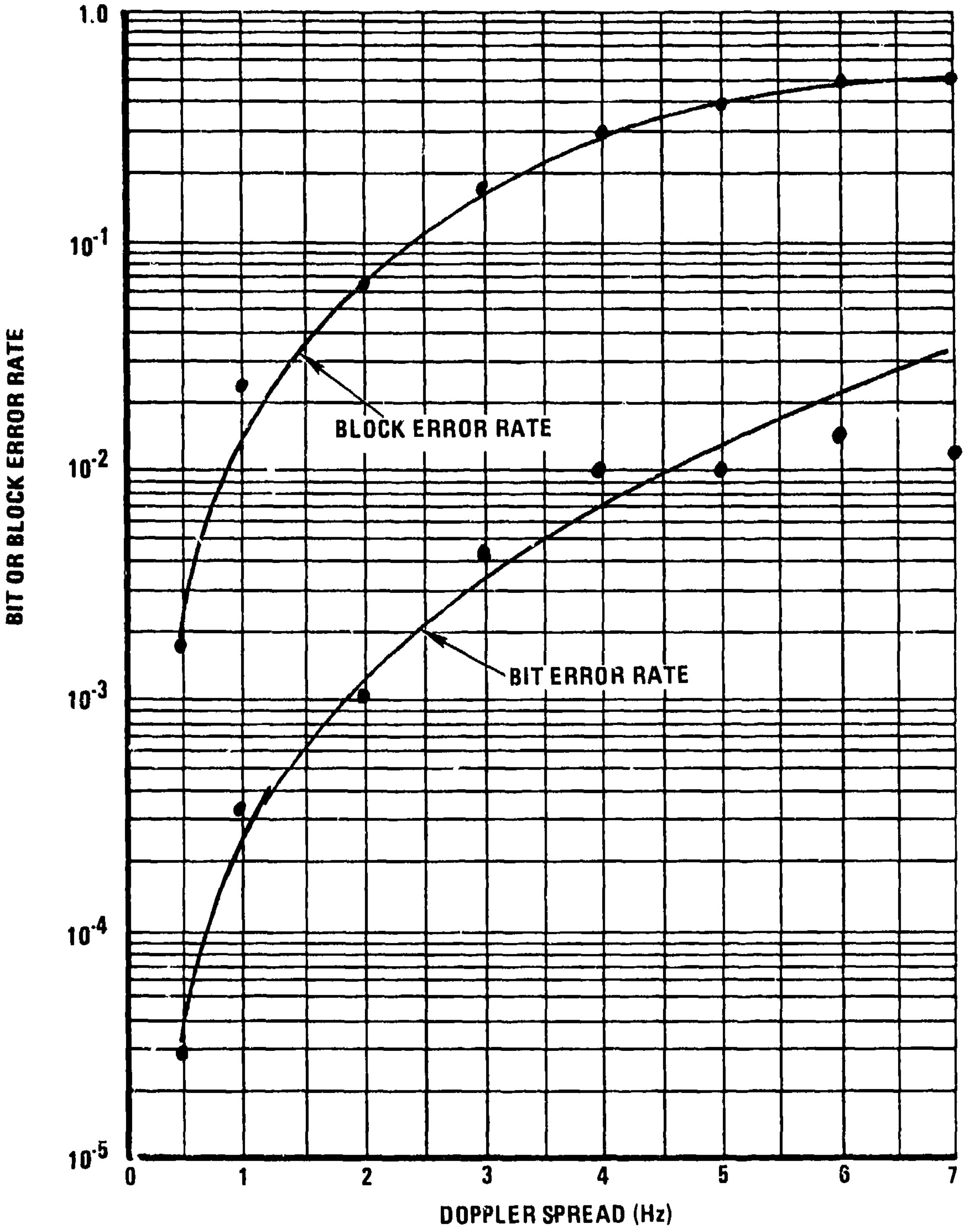

Figure 3.3.1-4. Single Fading Path With $E_{pb}/N_o = \infty$ at 8 kb/s

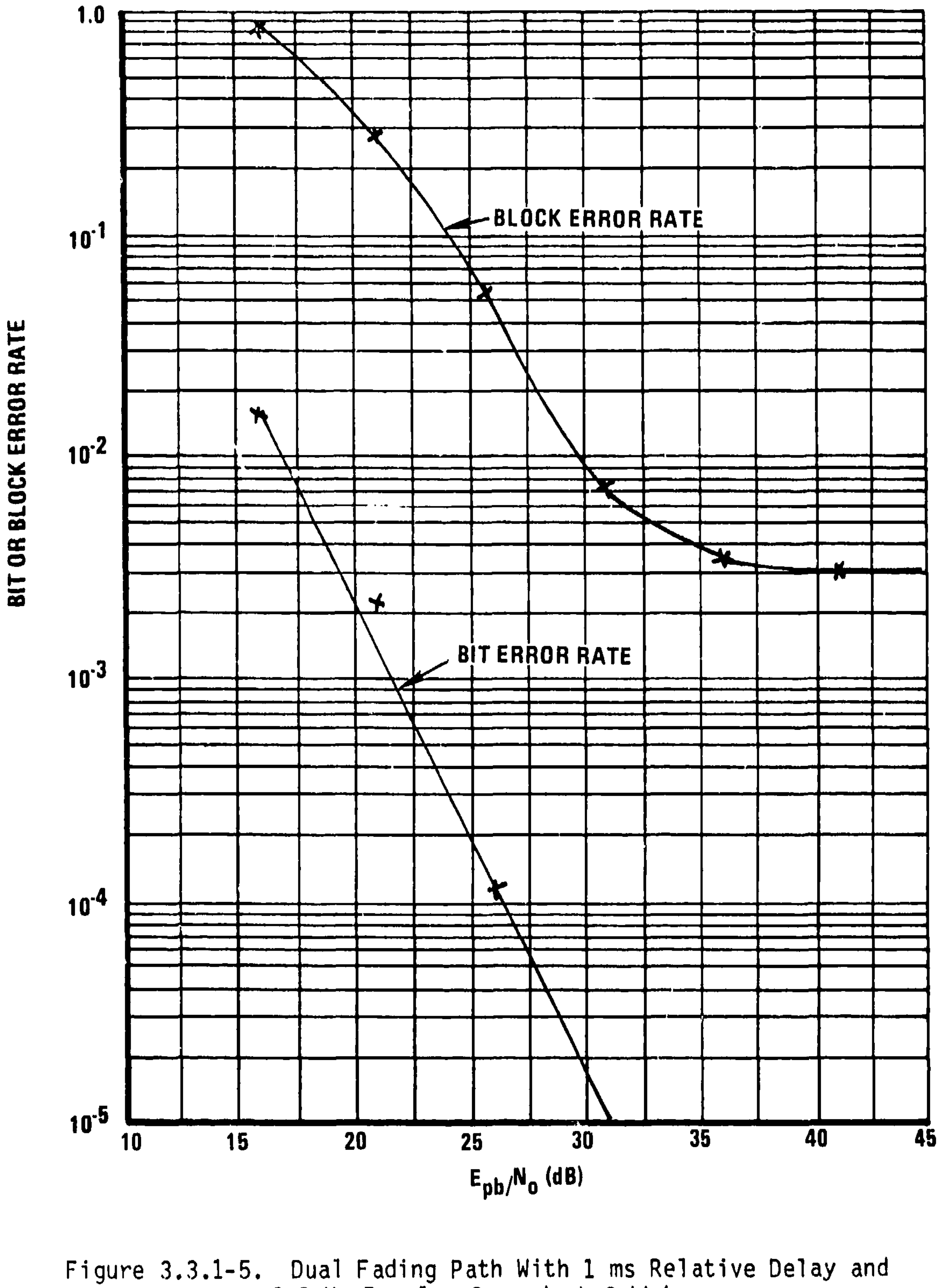

Figure 3.3.1-5. Dual Fading Path With 1 ms Relative Delay and 0.2 Hz Doppler Spread at 8 kb/s

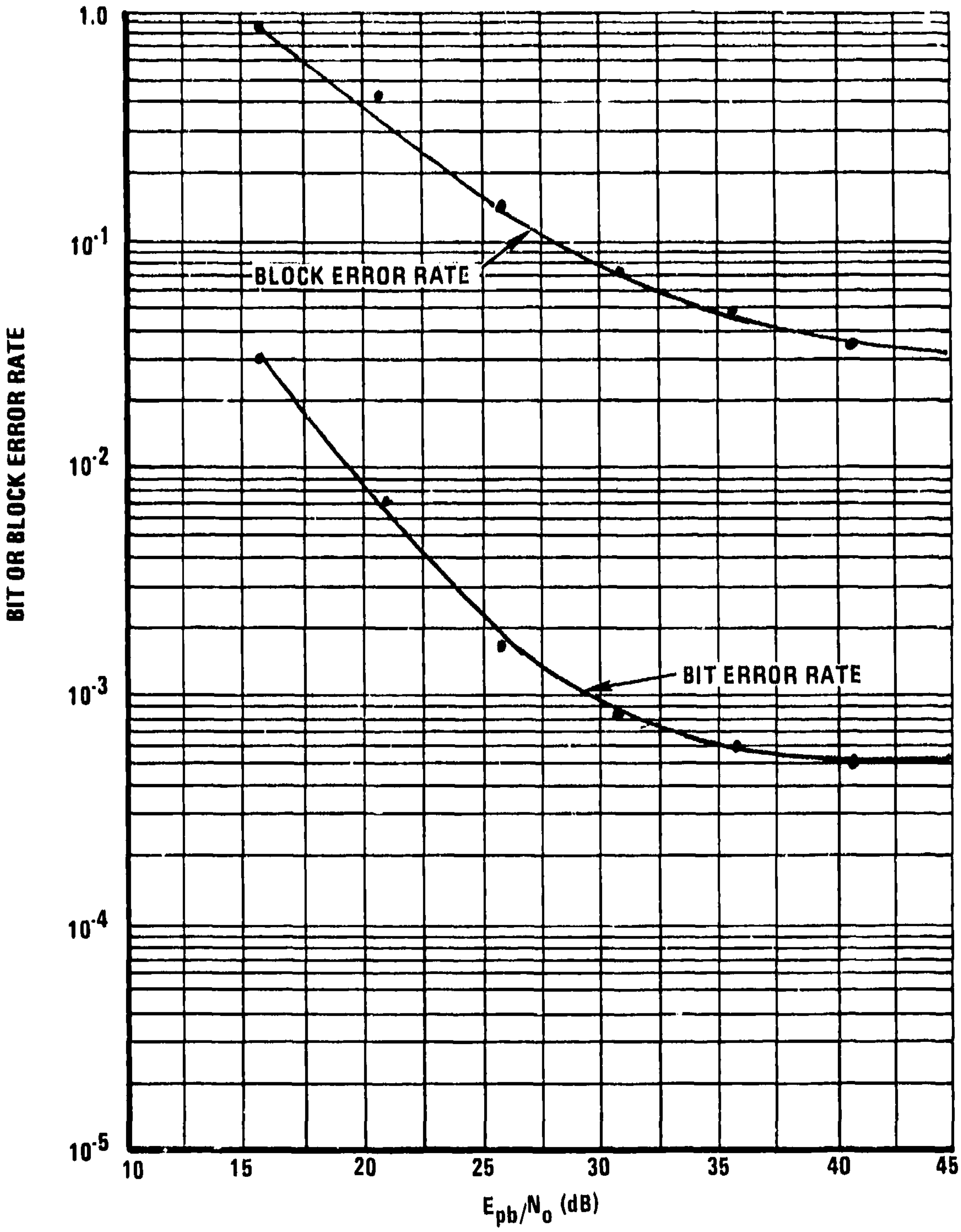

Figure 3.3.1-6. Dual Fading Path With 1 ms Relative Delay and 1.0 Hz Doppler Spread at 8 kb/s

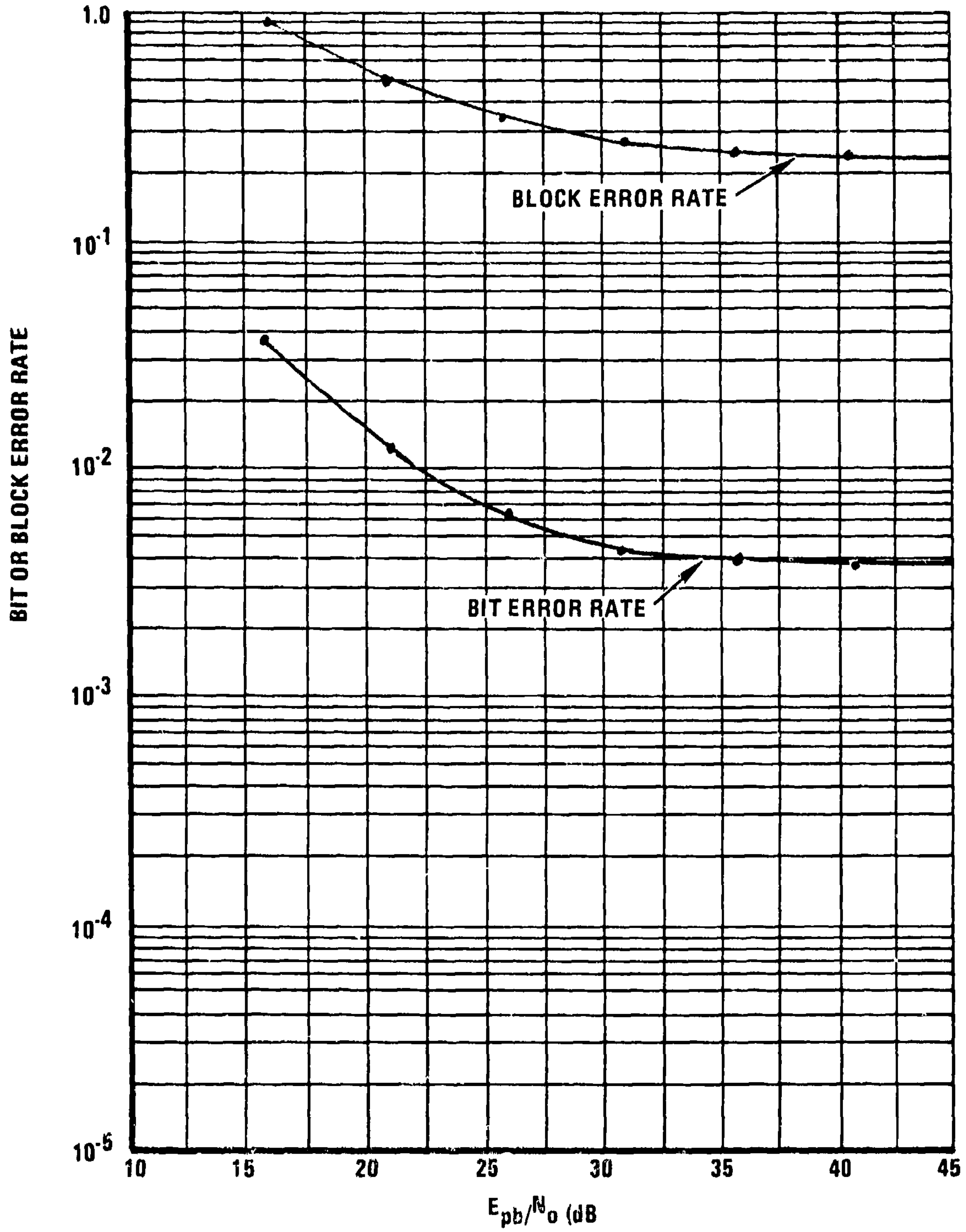

Figure 3.3.1-7. Dual Fading Path With 1 ms Relative Delay and 2.0 Hz Doppler Spread at 8 kb/s

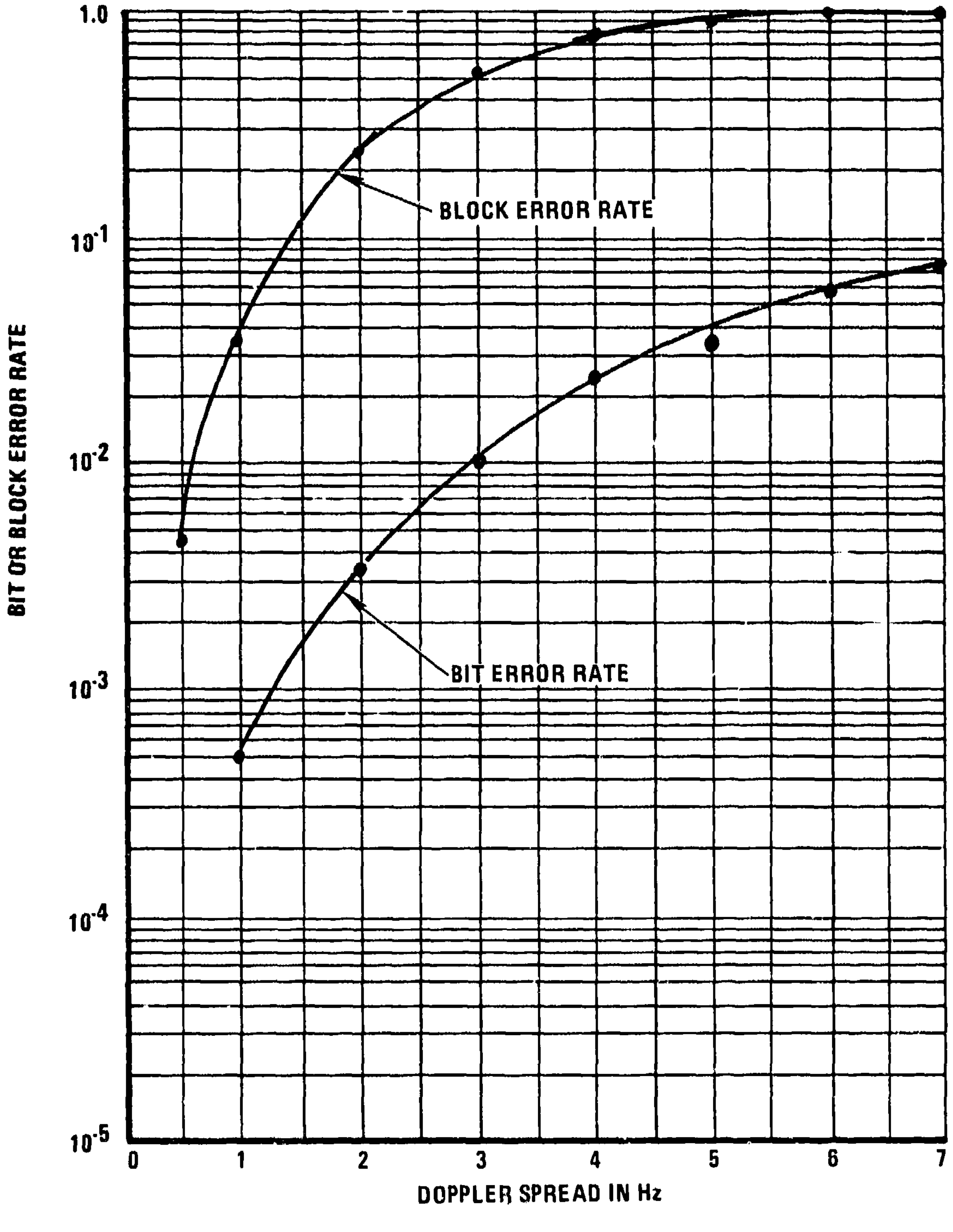

Figure 3.3.1-8. Dual Fading Path with 1 ms Relative Delay and $E_{pb}/N_0 = \infty$ at 8 kb/s

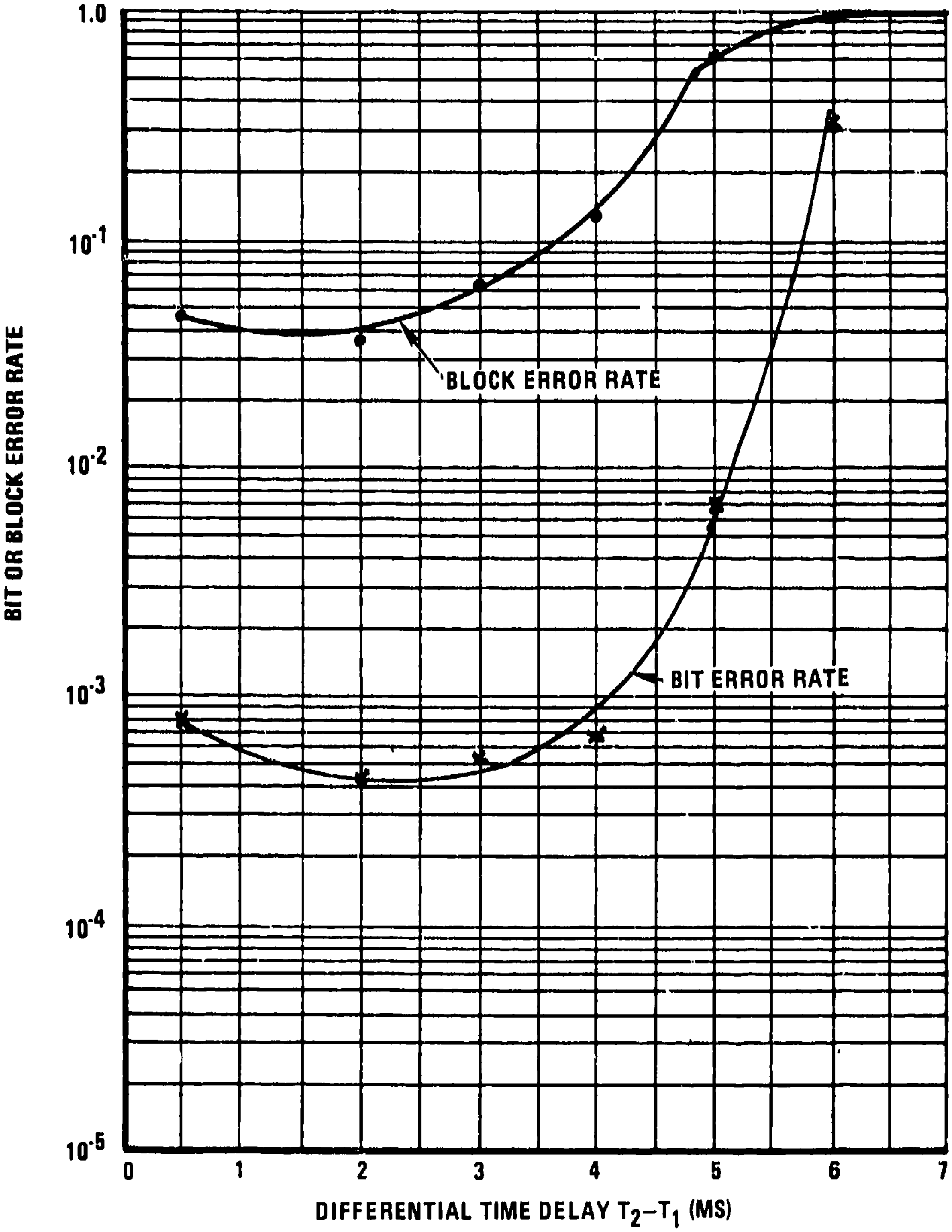

Figure 3.3.1-9. Dual Fading Path with 1.0 Hz Doppler Spread and $E_{pb}/N_o = \infty$ at 8 kb/s

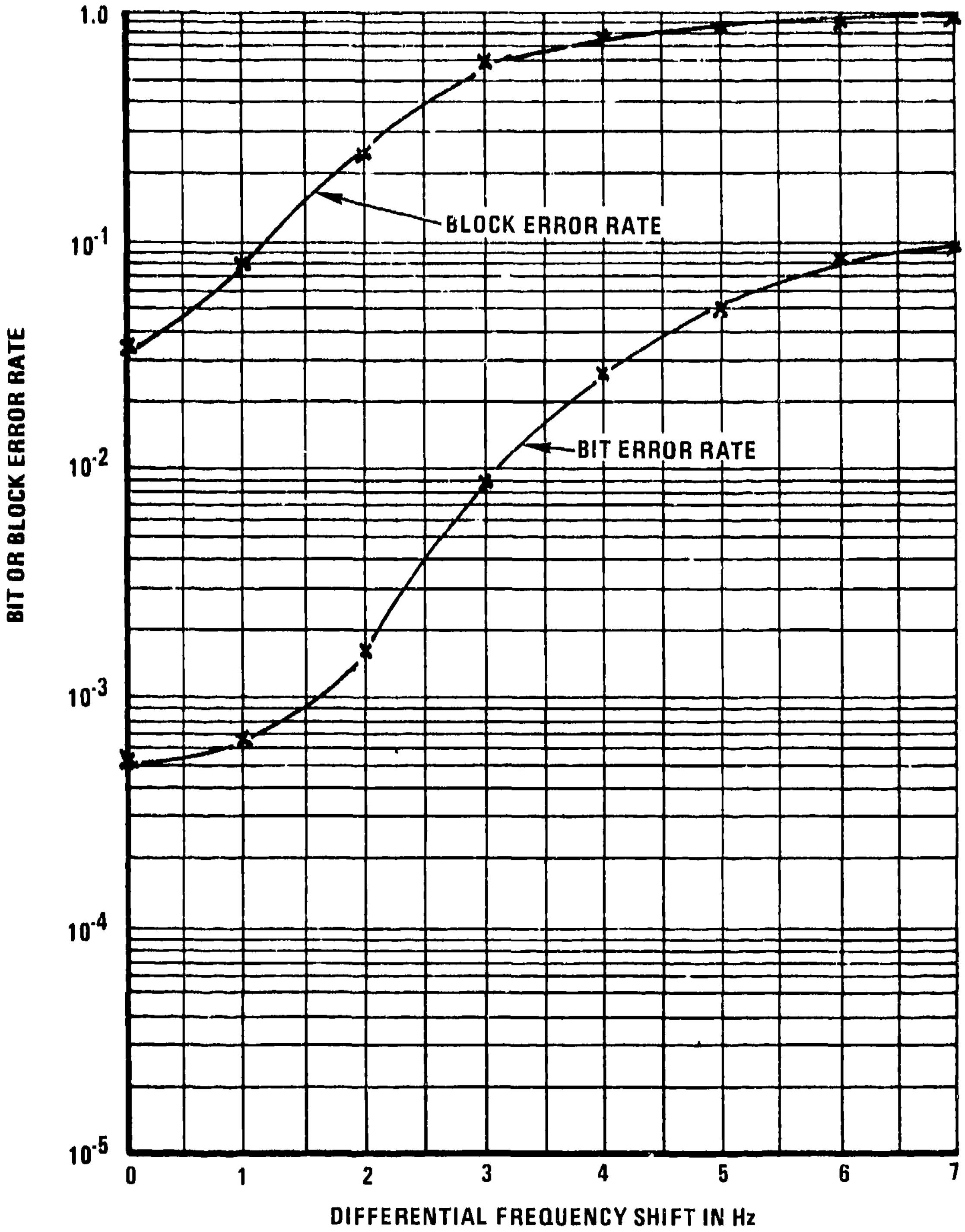

Figure 3.3.1-10. Dual Fading Path with 1 ms Relative Delay, 1 Hz Doppler Spread and $E_{pb}/N_o = \infty$ at 8 kb/s

Figure 3.3.2-1 shows the performance of the 16 kb/s mode for a single fading path with a Doppler Spread of 0.2 Hz versus E_{pb}/N_o. The performance is characterized with both transmit and receive filters in (as tested at the other data rates), with the receive filter bypassed and then the transmit filter also bypassed. One can observe from these curves that bypassing the receive filter substantially improves the modem performance, particularly for large values of E_{pb}/N_o. The improvement derived by removing the transmit filter is very small.

Figure 3.3.2-2 shows the performance for dual equal (mean) power fading paths with a Doppler Spread of 0.2 Hz and a relative delay spread of 1 ms versus E_{pb}/N_o. Again, performance for the three filter (bypass) conditions is characterized.

Similar performance improvements can be observed as each filter is bypassed. The improvement obtained when the transmit filter is bypassed, which was not present for the single path, is most likely due to the modem's ability to track the resulting impulsive multipath channel better.

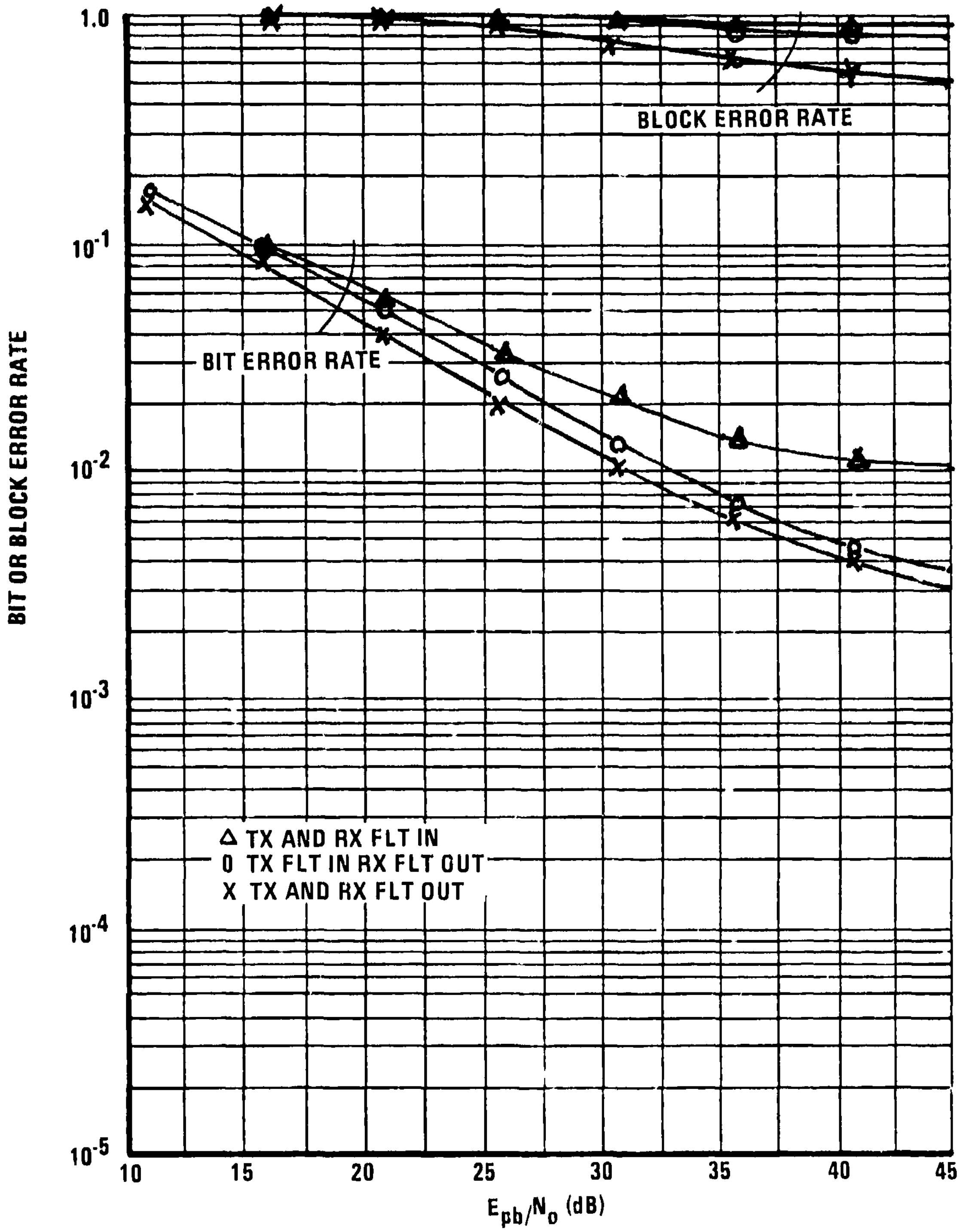

Figure 3.3.2-1. Single Fading Path With 0.2 Hz Doppler Spread at 16 Kbs

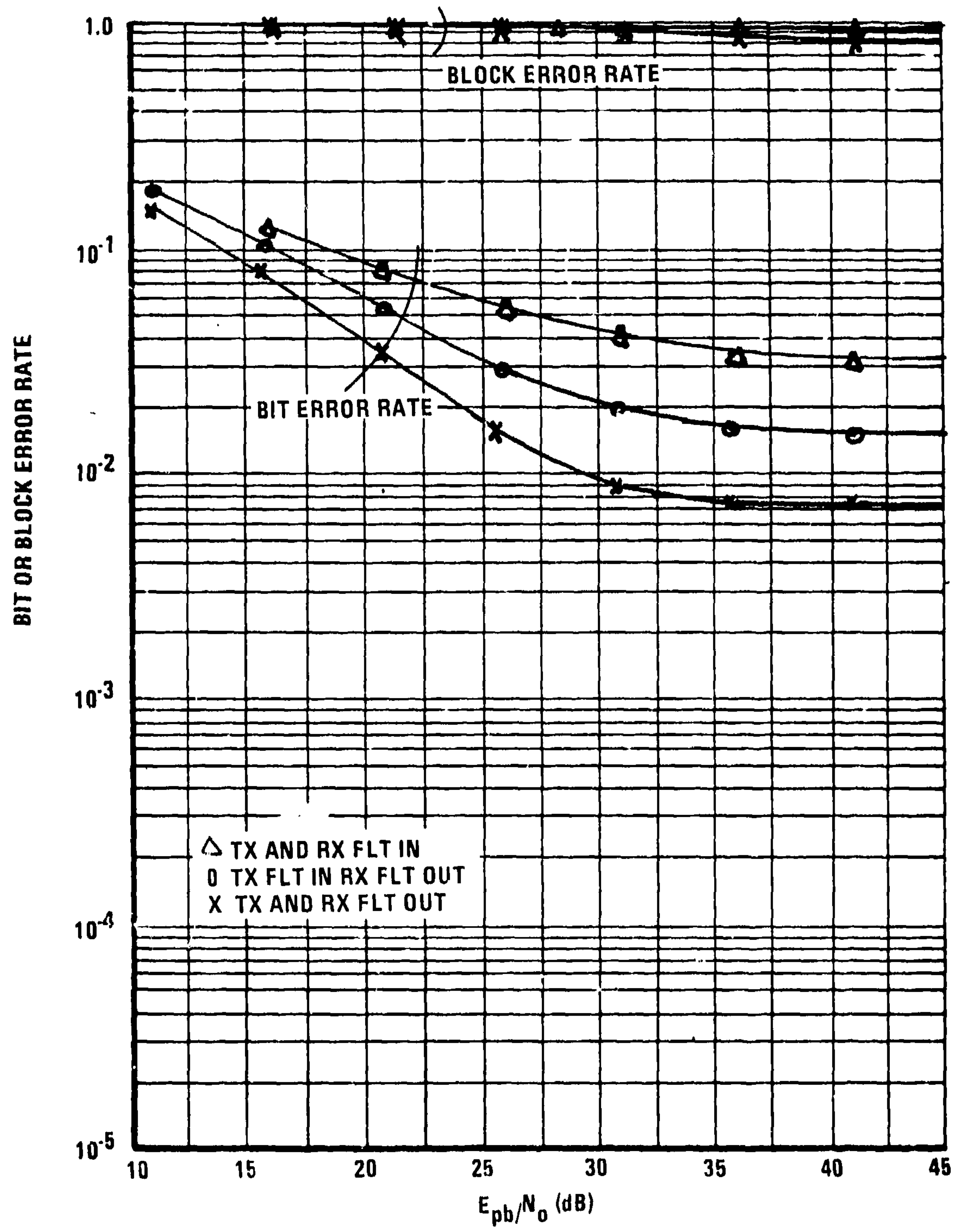

Figure 3.3.2-2. Dual Fading Path With 1 ms Relative Delay and 0.2 Hz Doppler Spread at 16 Kbs

4.0 RECOMMENDATIONS

The excellent performance results of the Harris narrowband HF modem operating at 4.8 kb/s strongly suggest that the addition of an interleaver (convolutional) coupled with a rate 1/2 Viterbi soft-decision coder-decoder would provide a very low ($< 10^{-6}$) BER throughput of 2.4 kb/s data. The interleaver and coder should be developed and implemented as part of the HF modem. Not only would this permit data grade communications at 2.4 kb/s over HF links, but high reliability 2.4 kb/s LPC secure voice transmission would be made possible. The substantial multipath spread capabilities of the Harris HF modem also permit a greater utilization of the HF band below the MUF.

To further evaluate the performance of the Harris HF modem in comparison with other HF modems, it is recommended that over-the-air tests be performed over an HF link from Ascension Island to Patrick Air Force Base. A proposed test plan these evaluations is presented in Appendix F.

APPENDIX A

PRELIMINARY TEST PLAN

(IN-PLANT TEST)

A1.0 SCOPE

This plan describes a test program for the HF Modem developed by Harris GCSD. The preliminary testing covered by this document will be conducted at Harris GCSD facilities in Melbourne, Florida. The final testing will be covered by a separate document and will be performed on RADC's HF simulator located in RADC's DICEF facility.

A2.0 OBJECTIVE

The objective of the preliminary testing is to demonstrate modem operation at 2.4, 3.6, and 4.8 kb/s over a 3 kHz channel and 8 and 16 kb/s over a 6 kHz channel. The HF channels (3 and 6 kHz) will be simulated on Harris GCSD's near real-time HF simulator. Final testing on RADC's HF simulator will cover the 3 kHz channel rates of 2.4, 3.6, and 4.8 kb/s.

A3.0 EQUIPMENT DESCRIPTION

The HF Modem hardware consists of a control processor and a fast array processor connected to an AMD 2900 microprocessor development system. The HF simulator is implemented as an additional program in the modem so that the modem takes turns being a link simulator and a modem. This, of necessity, requires nonreal-time operation. Figure A3.0 is a functional block diagram of the Harris HF simulator. It is mathematically modeled after the channel simulator at NTIA described by Watterson, et. al.[1,2] The actual channel simulation has three independently faded channels with selectable Doppler frequency shift and time delay available. The fading is

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[1] "Experimental Verification of an Ionospheric Channel Model", C.C. Watterson, J.R. Juroshek, W.D. Besema, July 1969, U.S. Department of Commerce Report, ERL 112-ITS80.

[2] "HF Channel-Simulator Measurements and Performance Analyses on the USE-10, ACQ-6, and MX190 PSK Modems," C. C. Watterson, C. M. Minister, July 1975, U.S. Department of Commerce Report, OT 75-56.

caused by multiplication of the delayed signal with a two-dimensional Gaussian vector whose components have been passed through a two-pole Butterworth filter. The Doppler Spread is calculated based upon the "RMS bandwidth" of the filter.

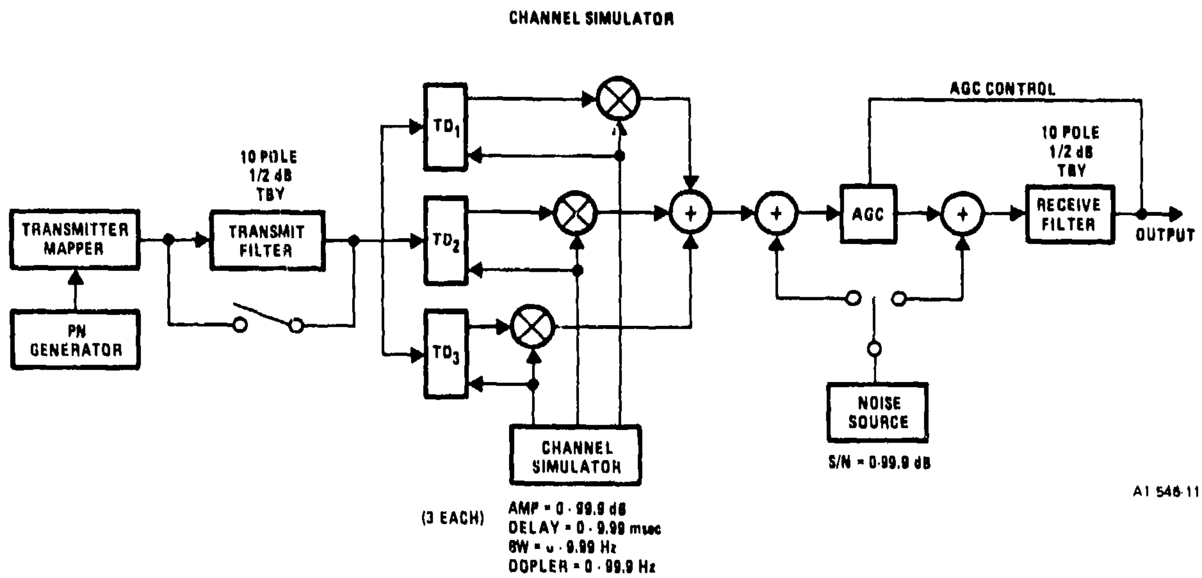

Figure A3.0. Channel Simulator

$$D_s = 2 \int_0^{\infty} w^2 \left| F^2 (w) \right| dw$$

where D_s is Doppler Spread and F(w) is the frequency response of the filter. For a two-pole Butterworth filter, this corresponds to the 3 dB bandwidth. The simulator at DICEF uses a three-pole filter for this purpose, but channel phase variation statistic can be shown to depend (on a first order basis) on the Doppler Spread as defined in the above equation independent of the shape of F(w). The simulator at NRL[3] uses a second order Butterworth filter like Harris.

[3] "A Programmable Real-Time HF Channel Simulator," R. Cole, W. Jewett, J. Linnchou, Jr.

The principal difference between the DICEF simulator and the Harris simulator, as shown, is that the RF modulated signal is created as a complex input and the bandpass filters associated with the transmitter and receiver, along with the receive AGC, are included in the channel model. The output is a complex demodulated signal representing the result of a QAM Demodulator at the receiver. This representation bypasses the need for Hilbert transformers and allows direct evaluation of RF equipment effects without the cumbersome task of obtaining and interfacing this gear. The effect of RF filters was felt to be an essential aspect of the channel disturbance of a high rate serial transmission technique since the "smearing" of the channel impulse response by the filter directly affects the amount of work an equalizer or correlator approach must do to combat channel disturbances.

A4.0 TEST PROGRAM

The preliminary testing will be done on the Harris GCSD HF simulator which operates about 1/14 of the real time. All preliminary testing will be done at Melbourne, Florida.

During the tests, the average bit error rate and the average block error (1000 bits to a block) will be measured as a function of the number of paths, S/N, Doppler Spread, and delay. Due to the non-real-time nature of the testing, the collection of data for a single data rate will take approximately 5 days based on statistically representative data. Since there are 5 data rates to be run, the preliminary testing will take approximately 25 days.

A4.1 Single Path Versus S/N

During this test, the Harris Modem will be tested over a single fading path with additive Gaussian noise as a disturbance. This test will be run for Doppler rates of 0.2 Hz, 1.0 Hz, and 2.0 Hz, and for data rates of 2.4, 3.6, and 4.8 kb/s (3 kHz channel), and 8.0 and 16.0 kb/s (6 kHz channel).

A4.2 Dual Path Versus S/N

During this test, the Harris Modem will be tested over two equal power fading channels with additive Gaussian noise as a disturbance. The test will be run for Doppler rates of 0.2 Hz, 1.0 Hz, and 2.0 Hz, and for data rates of 2.4, 3.6, and 4.8 kb/s (3 kHz channel), and 8.0 and 16.0 kb/s (6 kHz channel).

A4.3 Single Path Versus Doppler Spread

During this test, the Harris Modem will be tested over a single fading path with Doppler Spread as a disturbance. For this test, E_{bp}/N_o will be ∞ and the test will be run for Doppler Spreads of 0.5, 3.0, 4.0, 5.0, and 7.0 Hz, and for data rates of 2.4, 3.6, and 4.8 kb/s (3 kHz channel) and 8.0 and 16.0 kb/s (6 kHz channel).

A4.4 Dual Path Versus Doppler Spread

During this test, the Harris Modem will be tested over two equal power paths with Doppler Spread as a disturbance. For this test, E_{bp}/N_o will be set to ∞ and the test will be run for Doppler Spreads of 0.5, 2, 3, 4, 5, 6, and 7 Hz, and for data rates of 2.4, 3.6, and 4.8 kb/s (3 kHz channel) and 8.0 and 16.0 kb/s (6 kHz channel).

APPENDIX B

FINAL TEST PLAN

(DICEF TEST)

B1.0 SCOPE

This plan describes the test program for the HF Modem developed by Harris GCSD. The preliminary testing was covered in a previous document and conducted at Harris GCSD facilities in Melbourne, Florida. The final testing covered in this document will be performed on RADC's HF simulator located in RADC's DICEF facility.

B2.0 OBJECTIVE

The objective of the final test is to demonstrate modem operation at 2.4, 3.6, and 4.8 kb/s over a 3 kHz HF channel simulated on RADC's real-time HF simulator and correlate the results with those run during the in-plant test.

B3.0 EQUIPMENT DESCRIPTION

The HF Modem consists of a control processor, a fast array processor, and an analog interface all contained in a single chassis. The modem will be connected to the RADC HF simulator and instrumented as shown in Figure B3.0. The HP-1645A error analyzer provides the data stream for the transmitter and computes the error error rate at the receiver. The four channel recorder is used to record AGC control voltage, the lower half of the 3 kHz channel, the upper half of the 3 kHz channel, and the analog equivalent of the error rate. This allows simulatenous recording of fades which band the fade affected and the error rate associated with the fade. This is essentially the same instrumentation used by Harris during the over-the-air test between Rochester, New York and Quincy, Illinois.

A4.0 TEST PROGRAM

The final testing will be done on the RADC HF simulator located at the DICEF at RADC.

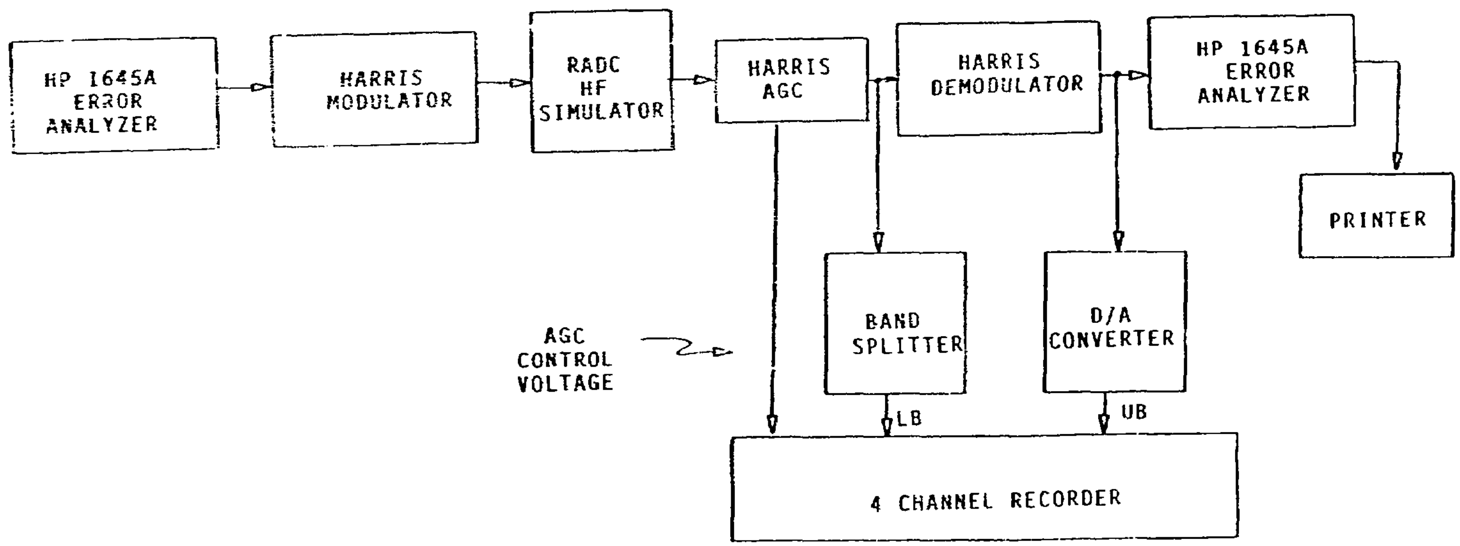

Figure B3.0. HF Final Test Setup

During the tests, the average bit error rate and the average block error (1000 bits to a block) will be measured as a function of the number of paths, S/N, Doppler Spread, and delay. In addition to the testing proposed by Harris in this test plan, Harris will also perform additional testing on channel models of RADC's choosing.

B4.1 Single Path Versus S/N (Gaussian)

During this test, the Harris Modem will be tested over a single fading path with additive Gaussian noise as a disturbance. This test will be run for Doppler rates of 0.2 Hz, 1.0 Hz, and 2.0 Hz, and for data rates of 2.4, 3.6, and 4.8 kb/s.

B4.2 Dual Path Versus S/N (Gaussian)

During this test, the Harris Modem will be tested over two equal power fading channels with additive Gaussian noise as a disturbance. The test will be run for Doppler rates of 0.2 Hz, 1.0 Hz, and 2.0 Hz, and for data rates of 2.4, 3.6, and 4.8 kb/s.

B4.3 Single Path Versus Doppler Spread

During this test, the Harris Modem will be tested over a single fading path with Doppler Spread as a disturbance. For this test, E_{bp}/N_o will be ∞ , and for data rates of 2.4, 3.6, and 4.8 kb/s.

B4.4 Dual Path Versus Doppler Spread

During this test, the Harris Modem will be tested over two equal power paths with Doppler Spread as a disturbance. For this test, E_{bp}/N_o will be set to ∞ and the test will be run with a delay of 1.0 ms, and for data rates of 2.4, 3.6, and 4.8 kb/s.

B4.5 Dual Path Versus Delay

During this test, the Harris Modem will be tested over two equal power paths with delay as a disturbance. For this test, E_{bp}/N_0 will be set to ∞ and the test will be run for a Doppler of 1.0 Hz and data rates of 2.4, 3.6, and 4.8 kb/s.

B4.6 Single Path Versus S/N (Atmospheric)

During this test, the Harris Modem will be tested over a single fading path with additive atmospheric noise as a disturbance. This test will be run for Doppler rates of 0.2 Hz, 1.0 Hz, and 2.0 Hz, and for data rates of 2.4, 3.6, and 4.8 kb/s.

B4.7 Dual Path Versus S/N (Atmospheric)

During this test, the Harris Modem will be tested over two equal power fading channels with additive atmospheric noise as a disturbance. The test will be run for Doppler rates of 0.2 Hz, 1.0 Hz, and 2.0 Hz, and for data rates of 2.4, 3.6, and 4.8 kb/s.

APPENDIX C

DICEF PARAMETERS

There are 10 parametric performance curves that were run at Harris on the Harris simulator and were repeated at DICEF. The DICEF parameters for these curves were:

Curve 1 - 0.2 Hz Single Fading Path Versus E_b/N_o

PATH 1, IONIC 1, SPREAD 0.1, SIGNAL, ON, 0, NOISE (OFF, ON -35, ON -30, ON -25, ON -20, ON -15)*

Curve 2 - 1 Hz Single Fading Path Versus E_b/N_o

PATH 1, IONIC 1, SPREAD 0.5, SIGNAL, ON, 0, NOISE (OFF, ON -35, ON -30, ON -25, ON -20, ON -15)

Curve 3 - 2 Hz Single Fading Path Versus E_b/N_o

PATH 1, IONIC 1, SPREAD 0.1, SIGNAL, ON, 0, NOISE (OFF, ON -35, ON -30, ON -25, ON -20, ON -15)

Curve 4 - .2 Hz Dual Fading Path Versus E_b/N_o

PATH 1, IONIC 1, SPREAD 0.1, SIGNAL, ON, -3, NOISE (OFF, ON -38, ON -33, ON -28, ON -23, ON -18)

PATH 2, IONIC 1, SPREAD 0.1, DELAY 1000, SIGNAL, ON, -3, NOISE (OFF, ON -38, ON -33, ON -28, ON -23, ON -18)

Curve 5 - 1 Hz Dual Fading Path Versus E_b/N_o

PATH 1, IONIC 1, SPREAD 0.5, SIGNAL, ON, -3, NOISE (OFF, ON -38, ON -33, ON -28, ON -23, ON -18)

PATH 2, IONIC 1, SPREAD 0.5, DELAY 1000, SIGNAL, ON, -3, NOISE (OFF, ON -38, ON -33, ON -28, ON -23, ON -18)

*The values entered for noise for 4.8 kb/s runs were those given. Since the noise occurs in a 4.3 kHz effective bandwidth, the actual values of E_b/N_o are 0.47 dB less than the numbers entered. The values entered for 2.4 kb/s runs were 2.53 dB less or (OFF, ON -32.47, -27.47, -22.47, -17.47, -12.47). For 3.6 kb/s runs, these values were (OFF, ON -33.81, -28.81, -23.81, -18.81, -13.81). These provide for values of E_b/N_o equal to (∞ , 35, 30, 25, 20, 15) respectively. For dual path runs, these values are increased by 3 dB.

All curves were run for the 2.4 kb/s and and 4.8 kb/s rates. Only curve 5 was run for the 3.6 kb/s rate.

Curve 6 - <u>2 Hz Dual Fading Path Versus E_b/N_o</u>

PATH 1, IONIC 1, SPREAD 1, SIGNAL, ON, -3, NOISE (OFF, ON -38, ON -33, ON -28, ON -23, ON -18)

PATH 2, IONIC 1, SPREAD 1, DELAY 1000, SIGNAL, ON, -3, NOISE (OFF, ON -38, ON -33, ON -28, ON -23, ON -18)

Curve 7 - <u>Single Fading Path Versus Doppler Spread</u>

PATH 1, IONIC 1, SPREAD (0.25, 1.5, 2, 2.5, 3, 3.5, 4), SIGNAL ON 0, NOISE OFF

Curve 8 - <u>Dual Fading Path Versus Doppler Spread</u>

PATH 1, IONIC 1, SPREAD (0.25, 1.5, 2, 2.5, 3, 3.5, 4), SIGNAL ON -3, NOISE OFF

PATH 2, IONIC 1, SPREAD (0.25, 1.5, 2, 2.5, 3, 3.5, 4), DELAY 1000, SIGNAL ON -3, NOISE OFF

Curve 9 - <u>Dual Fading Path Versus Delay Spread</u>

PATH 1, IONIC 1, SPREAD 0.5, SIGNAL ON -3, NOISE OFF

PATH 2, IONIC 1, SPREAD 0.5, DELAY (500, 2000, 3000, 4000, 5000, 6000, 7000), SIGNAL ON -3, NOISE OFF

Curve 10 - <u>Dual Fading Path Versus Differential Doppler</u>

PATH 1, IONIC 1, DOPPLER 0, SPREAD 0.1, SIGNAL ON -3, NOISE OFF

PATH 2, IONIC 1, DOPPLER (1, 2, 3, 4, 5, 6, 7), SPREAD 0.5, DELAY 1000, SIGNAL ON -3, NOISE OFF

In addition to the above data, curve 9 was run for both 4.8 kb/s and 2.4 kb/s with the AXEL telephone simulator in tandem with the DICEF. The AXEL settings will be on both C2 and 3002 and all other impairments will be off.

In addition to the above data, curves for certain pathological cases were run. These were:

Curve 11 - Dual Fading Unbalanced Path

PATH 1, IONIC 1, DOPPLER -0.5, SPREAD 0.05, SIGNAL ON -16, NOISE (OFF, ON -35, ON -30, ON -25, ON -20, ON -15)

PATH 2, IONIC 1, DOPPLER 0.5, SPREAD 0.05, DELAY 1200, SIGNAL ON 0, NOISE (OFF, ON -35, ON -30, ON -20, ON -15)

Curve 12 - Dual Fading Equal Path

PATH 1, IONIC 1, SPREAD 0.2, SIGNAL ON -3, NOISE (OFF, ON -35, ON -30, ON -25, ON -20, ON -15)

PATH 2, IONIC 1, SPREAD 0.2, DELAY 1000, SIGNAL ON -3, NOISE (OFF, ON -35, ON -30, ON -25, ON -15)

Curve 13 - Triple Fading Path 1

PATH 1, IONIC 1, DOPPLER -0.5, SPREAD 0.05, SIGNAL ON -26, NOISE (OFF, ON -40, ON -35, ON -30, ON -25)

PATH 2, IONIC 1, SPREAD 0.05, DELAY 600, SIGNAL ON -12, NOISE (OFF, ON -40, ON -35, ON -30, ON -25)

PATH 3, IONIC 1, DOPPLER 0.5, SPREAD 0.05, DELAY 2800, SIGNAL ON -14, NOISE OFF

Curve 14 - Triple Fading Path 2

PATH 1, IONIC 1, DOPPLER -1, SPREAD 0.1, SIGNAL ON -14, NOISE (OFF, ON -35, ON -30, ON -25, ON -20, ON -15)

PATH 2, IONIC 1, SPREAD 0.1, DELAY 600, SIGNAL ON 0, NOISE (OFF, ON -35, ON -30, ON -25, ON -20, ON -15)

PATH 3, IONIC 1, DOPPLER 1, SPREAD 0.1, DELAY 2800, SIGNAL ON -2, NOISE OFF

Curve 15 - Impulsive Noise

To be specified

APPENDIX D

RUN DURATION

Duration of Run (in Minutes) for Each Successive Data Point of the Test Curves

CURVE NUMBER	
1	30, 20, 20, 15, 15, [illegible]
2	15, 10, 10, 5, 5, 5
3	10, 10, 5, 5, 5, 5
4	30, 20, 20, 15, 15, 15
5	15, 10, 10, 5, 5, 5
6	10, 10, 5, 5, 5, 5
7	25, 10, 10, 5, 5, 5, 5
8	25, 10, 10, 5, 5, 5, 5
9	15, 15, 10, 10, 5, 5, 5
10	15, 15, 10, 10, 5, 5, 5
11	30, 20, 20, 15, 15, 10
12	20, 15, 15, 10, 10, 10
13	20, 20, 15, 10, 10
14	30, 20, 20, 15, 15, 10
15	To be specified

APPENDIX E

OPERATIONAL MODES

Operational Modes Tested Each of the Test Curve Conditions

CURVES	2.4 kb/s	3.6 kb/s	4.8 kb/s	2.4 kb/s TANDEM WITH AXEL	4.8 kb/s TANDEM WITH AXEL
1	X		X		
2	X		X		
3	X		X		
4	X		X		
5	X	X	X		
6	X		X		
7	X		X		
8	X		X		
9	X		X	X	X
10	X		X		
11	X		X		
12	X		X		
13	X		X		
14	X		X		
15	X		X		

X indicates test performed.

APPENDIX F

LINK TEST PLAN

LINK TEST PLAN

PURPOSE

It is recommended that a test of the Harris HF Modem be conducted over an HF link from Ascension Island to Patrick Air Force Base. The purpose of this test would be:

a. Compare the bit error performance of the Harris Modem, the RADC (GTE) Modem, and the USC-12 presently installed on the Eastern Test Range.

b. Determine the effect of the VODAT rate 1/2 Golay Coder on the BER of the Harris and Sylvania Modems.

c. Determine the available frequency range for each modem which allows satisfactory bit error rate.

TEST ARRANGEMENTS

The transmit terminals for all modems will be located at Ascension Island. The receive terminals for all modems will be located at the Communications facility at the Eastern Test Range. The average power levels of all modems will be adjusted to provide the same peak output power from the power amplifier in Ascension.

The tests would be conducted at a particular frequency for a 30-minute period. Both upper and lower sidebands will be used so that two modems will be tested simultaneously. Every ten minutes the modems will be swapped such that each of the three modems will have been operated for 10 minutes on the upper sideband and 10 minutes on the lower sideband during the 30-minute period.

Frequencies will be chosen to span the range between the predicted MUF and the predicted LUF. In all cases, the average bit error rate and block error rate will be recorded using two HP-16425A error analyzers and an appropriate printer for each modem. Block error rate based upon 1000 bit blocks will also be measured.

Other instrumentation to monitor the link parameters effectively will probably not be possible since the HF receivers are remotely located from the modem site. This should not be viewed as too great a loss, however, since the objective is to determine the relative suitability of the modems for the purposes of ETR data transmission. Error rates with and without the VODAT will be recorded, but those with the VODAT will take precedence. The weights on the Harris Modem will be displayed (along with the eye pattern) when the modem is operated to better determine the channel characteristics.

It is anticipated that the on-the-air tests span 5 working days. Since 3 days should be allowed for transportation and setup, an 8-day test is recommended.

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